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Practical Aspects of Photovoltaic Technology, Applications, and Cost (Revised)

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Louis Rosenblum
University of Michigan

August 1985

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
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PREFACE

The following text was prepared by Dr. Louis Rosenblum, who earned a Ph.D. in Chemistry in 1952 from Ohio State University, and who was a graduate of the NASA Nuclear Engineering School in 1957. His career at the NASA Lewis Research Center began in 1952 as a Research Scientist, then Technical Supervisor. From 1969 to 1977 he was Chief of the Direct Energy Conversion Division and from 1977 until his retirement from NASA in 1981 he was Chief of the Solar and Electrochemistry Division. He has either worked personally or overseen research in technology development for space and terrestrial applications of photovoltaic devices. He has written some thirty scientific articles or documents and has chaired or served on a number of panels, conferences and committees related to solar energy applications. Since 1981, Dr. Rosenblum has worked as a private consultant for U.S. governmental agencies, international bodies, private organizations, and educational institutions.

Dr. Rosenblum was commissioned to write this text under an unsolicited grant from the U.S. National Aeronautics and Space Adminisration, Lewis Research Center, administered from the Center for Afroamerican and African Studies at the University of Michigan, with Dr. Allen F. Roberts as Principal Investigator. The grant, "Research on Social Aspects of Photovoltaic Applications," has as a major goal the dissemination of ideas and information concerning the nature and impact of photovoltaic technology. It is hoped that this document and the seminars during which it is presented will assist all concered in the achievement of full and appropriate use of this technology of great promise.

CONTENTS

Section	Page
1.0 Introduction	1-1
2.0 Photovoltaic Power Systems	2-1
2.1 Solar Collector Type	2-1
2.2 Nominal Electrical Output	2-3
2.3 Extent of Autonomy	2-3
2.4 System Focus	2-4
3.0 Single Crystal Silicon Solar Cell, Flat-Plate Collectors	3-1
3.1 Solar Cells	3-1
3.1.1 Operation	3-1
3.1.2 Efficiency	3-2
3.1.3 Current-Voltage Characteristics	3-5
3.1.4 Manufacture	3-10
3.2 Modules, Panels, and Arrays	3-14
3.2.1 Definitions and Nomenclature	3-14
3.2.2 Module Efficiency	3-17
3.2.3 Module Operational Losses	3-22
3.2.4 Design, Fabrication, and Manufacture	3-25
3.2.5 Module Reliability	3-38
4.0 Storage Batteries	4-1
4.1 Role of Storage Battery	4-1
4.2 PV Battery Duty Cycle	4-3
4.3 Commercial Battery Types	4-5
4.4 Stand-Alone PV System Batteries	4-7

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CONTENTS (Continued)

Section	Page
5.0 Regulators and Controls	5-1
5.1 Regulators	5-1
5.2 Controls	5-6
5.2.1 Battery and Load Protection	5-6
5.2.2 Maximum Power Tracking	5-7
6.0 Instrumentation	6-1
6.1 Purposes	6-1
6.2 Types	6-2
7.0 Safety	7-1
7.1 Electrical Shock	7-1
7.2 Battery	7-2
7.3 Load Equipment	7-3
7.4 Lightning	7-3
8.0 Installation, Operation, and Maintenance	8-1
8.1 Site Survey	8-1
8.2 Installation and Checkout	8-1
8.3 Operation and Maintenance	8-5
9.0 Loads	9-1
9.1 Types	9-1
9.2 Selection	9-1
9.3 Energy Requirements	9-4
9.4 Management	9-4
9.5 AC vs. DC	9-6

CONTENTS (Continued)

Section		Page
10.0	Applications	10-1
10.1	Experience	10-1
10.2	Tangaye Village PV Demo Project	10-6
10.3	Future Trends	10-14
10.3.1	Near-Term	10-14
10.3.2	Far-Term	10-17
11.0	Service Performance	11-1
11.1	Reliability	11-1
11.2	Availability	11-2
11.3	Voltage Control	11-4
11.4	Comparison of Electrical Systems	11-4
11.4.1	Central Station Electric Grid	11-4
11.4.2	Diesel-Generator	11-6
11.4.3	PV Stand-Alone	11-7
12.0	System Preliminary Sizing	12-1
12.1	Average Daily Insolation	12-1
12.1.1	Description	12-1
12.1.2	Data	12-3
12.1.3	Worst-Month Average Daily Insolation	12-5
12.2	Overall System Efficiency	12-6
12.3	System Sizing Procedures	12-7
12.3.1	PV System Without Battery	12-7
12.3.2	PV System With Battery	12-8
12.4	Simplified Method for Preliminary System Sizing	12-10
12.5	Sizing for the Minimum Cost System	12-16
12.6	Sizing for Variable Load Demand	12-19
12.7	Comparison of Sizing Procedures	12-21
12.8	Significance of LOEP Values	12-24

CONTENTS (Continued)

Section		Page
13.0	System Cost	13-1
13.1	Capital Cost	13-1
13.1.1	PV System With Battery	13-1
13.1.2	PV System Without Battery	13-5
13.2	Module and BOS Costs	13-6
13.3	Levelized Energy Cost	13-8
Appendices		
A	Glossary	A-1
B	Terrestrial PV Measurement Procedures	B-1
C	Sample PV Battery Technical Data Sheet	C-1
D	Sample Site Inspection Check List	D-1
E	Installation and Maintenance Manual	E-1
F	Battery Installation and Operating Instructions	F-1
G	Maps of World Distribution of Solar Radiation	G-1
H	Tables of Average Daily Insolation for Selected Locations	H-1

1.0 INTRODUCTION

There appears to be no single or simple answer to the energy dilemma of developing countries; it is likely that a mixture of mutually supporting technical, institutional and developmental approaches will be needed. With regard to technical approaches, a most promising one, particularly for rural development, appears to be photovoltaic energy conversion by means of flat-plate photovoltaic systems.

Contrary to popular belief, a photovoltaic (PV) system does not embody a large amount of "high technology." The "high technology" is to be found in the solar cell. The rest of the system--array structure, wiring, controls, battery, etc.,--consists of conventional, "off-the-shelf" materials and components. Similarly, physical integration of the materials and components into a system involves moderate- to low- skilled labor and standard assembly and installation techniques. Characteristically, flat-plate PV systems have other desirable features: modularity, no moving parts, low maintenance requirements, and potential for long life.

In principle, flat-plate PV power systems have attributes that lend themselves to use for a variety of electrical energy needs in the developing countries. In practice, however, can PV systems meet these expectations? More specifically, can PV systems compete with conventional electric power generating systems in performance and cost? If so, under what conditions and when?

Practical questions call for practical answers. The purpose of this book is to equip the interested reader with the background, understanding, and computational tools with which to formulate practical answers. To this end the reader will find in the succeeding sections discussion of the following subjects: technology and operating performance of flat-plate PV systems and major subsystems and components; PV applications and operating experience; a procedure for the rapid sizing of systems; and present system costs and future

cost trends. With regard to the last two items, the text contains original material by the author that provides an objective approach to system sizing and cost comparison based on design service performance.

The original edition of this volume was used as the text for seminars on photovoltaic technology conducted by the author in several developing countries during 1983 and 1984: Guyana, Kenya, Ecuador, and Zimbabwe, as part of the USAID/NASA/Host Country Rural Medical System Project; and Gabon, as part of the Gabon/U.S. DOE/NASA Joint Program of Demonstration of Solar Photovoltaic Power.

The present revised edition provides an updating and enlargement of section 12, System Preliminary Sizing, and section 13, System Cost.

2.0 PHOTOVOLTAIC POWER SYSTEM

A photovoltaic (PV) power system is the totality of components needed to provide a required amount of electric power effectively and safely. A typical system may include (1) solar cell modules, (2) array structure and foundations, (3) voltage regulators and other controls, (4) storage battery and enclosure, (5) instruments, (6) power cables, buses and switchgear, (7) electrical grounding network, and (8) security fence (Fig. 2-1 and 2-2). Electrical loads are not usually included as a component of the power system.

PV systems are classified on the basis of certain operational or functional features: solar collector type, nominal electrical output, and extent of autonomy in supplying electrical loads. These are briefly discussed below.

2.1 Solar Collector Type

(1) Flat-Plate. This is a collector employing solar cells interconnected and packaged in planar modules. The collector is generally non-tracking but tilt angle may be seasonally adjusted. Flat-plate PV systems utilize single crystal silicon cells. They are derived from 25 years of space PV technology development and application, 20 years of terrestial PV system testing and development, and over a decade of commercial terrestrial PV development.

(2) Concentrator. This usually consists of one- or two-axis sun tracking collector with active or passive cooling of the solar cells. Sunlight is concentrated by the collector and focused on the solar cells. The most widely investigated collector types are the linear parabolic trough, the line focus Fresnel, and the point focus Fresnel. Collectors and the associated component technologies are still in the test and development stages. A limitation of concentrator systems is that they utilize only the direct component of solar radiation. For this reason such systems may not be suitable in many regions of the world which experience many cloudy, or partially cloudy, days during the year (Refs. 2-1 and 2-2).

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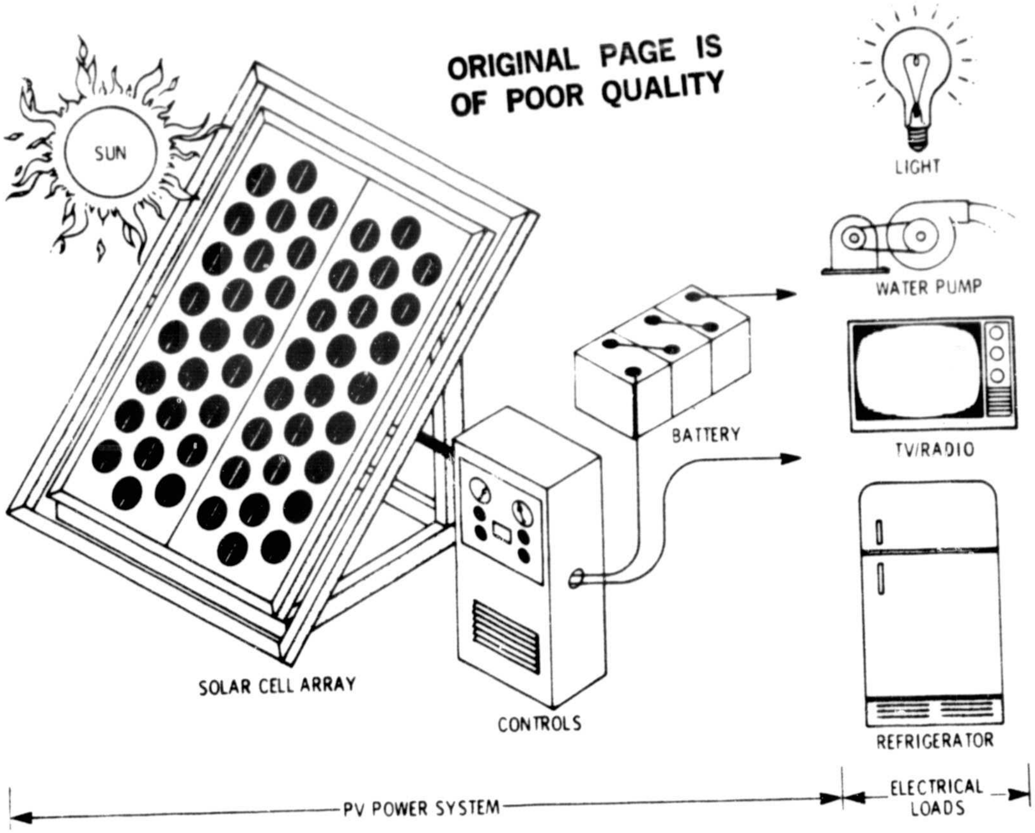

Figure 2-1 Schematic of a Stand-Alone PV Power System

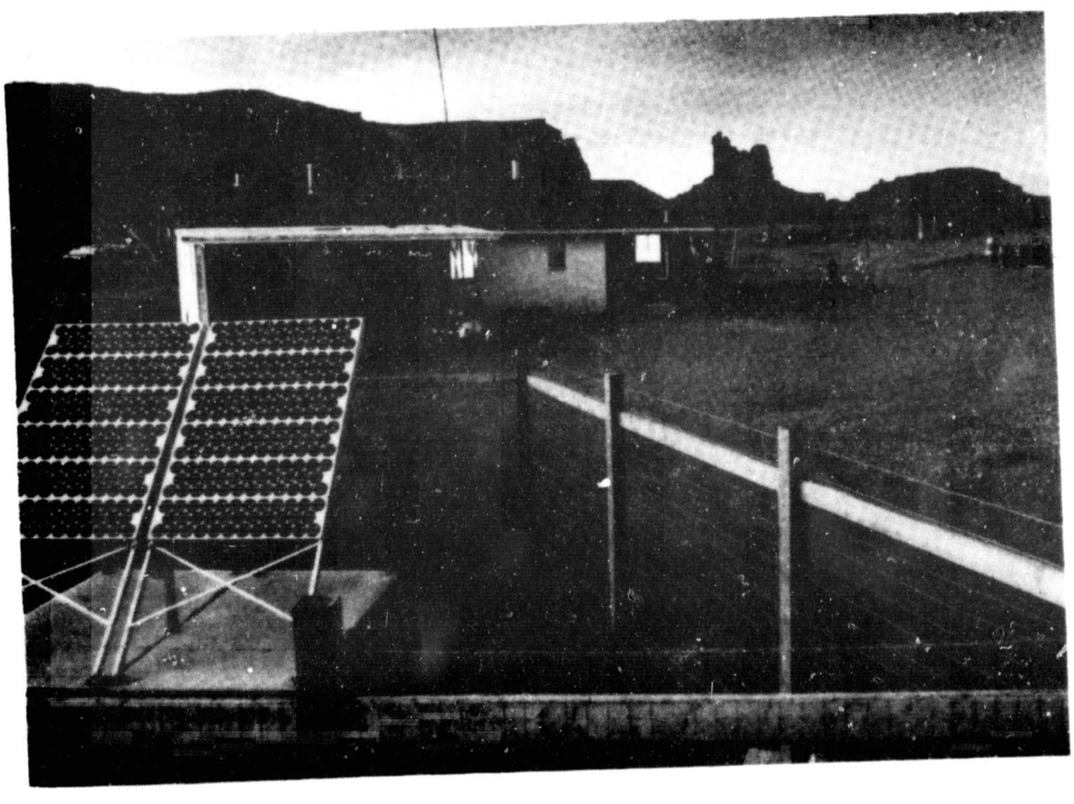

Figure 2-2 PV System Powering a Navajo Indian Home in Arizona (ARCO Solar Photo)

2.2 Nominal Electrical Output

(1) Quantity. The power output of a PV system has customarily been expressed in terms of peak power, e.g., peak watts (W_p). Peak power is, loosely speaking, the amount of power produced by the system at noon on a clear day with the collector facing directly toward the sun. More precisely, it is the amount of power produced at standard test conditions (STC), viz., receiver temperature of 28°C and 1 kW/m^2 solar irradiance. Since peak power represents a singular value of the rate of electrical energy generation at STC, it is an indefinite measure of the overall output. A more satisfactory measure of PV system output is the quantity of electrical energy generated over some time interval, e.g., kilowatt-hours per day (kWH/day) or megawatt-hours per year (MWH/yr). Use of an energy generation rate provides a measure of average power generation that reflects the variability--daily, seasonal and annual--of the solar resource.

2) Direct or Alternating Current. Solar cells produce direct current (d.c.). If an alternating current (a.c.) output is desired, an additional component, an inverter, must be added to the PV system to transform d.c. to a.c.

2.3 Extent of Autonomy

(1) Stand-Alone System. This is an independent power generating system which solely supplies local electrical loads. To date, almost all PV systems placed in service in remote and rural areas of the world have been of the stand-alone type.

(2) Grid-tied System. This consists of one of more power generating units feeding an electrical transmission and distribution network that provides power to a large number of widely dispersed loads. Conceptually, the several power generating units may be (a) all of the same variety, e.g., all PV systems or (b) mixed, for example, PV with diesel-generators, PV with mini-hydro generators, PV with fossil-fueled thermal generators, and so forth. To date, experience with grid-tied systems has been limited.

2.4 System focus

The prime objective of this text is to provide practical information about PV systems that are intended for use in development. Since most developing countries can ill-afford to invest in speculative, poorly designed, or technically deficient systems, only those types of system employing mature technology and having a proven track record in a diversity of applications will be discussed herein. On this basis PV concentrator systems are excluded. To date, there has been no commercial (i.e., economically viable) application of a concentrator system (Ref. 2-3). Major advances are needed in present concentrator system technology, in particular, technology related to solar cell and system efficiency and component reliability in order to achieve costs required for commercial feasibility (Ref. 2-4).

Therefore, the focus of this work will be on stand-alone, single crystal silicon solar cell, flat-plate, PV systems in the range of 1-40 kWH/day output.

SECTION 2
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3.0 SINGLE CRYSTAL SILICON SOLAR CELL, FLAT-PLATE COLLECTORS

3.1 Solar Cells

Solar cells convert light directly into electricity by a process called the photovoltaic effect. The first observation of this phenomenon was made by a French scientist, Edmund Becquerel, in 1839. Albert Einstein, in 1905, laid the theoretical foundation for understanding the PV effect. Yet it was not until 1954 that the first practical solar cell was fabricated by a group of scientists at the Bell Laboratory in the U.S. Improvements since then have led to the present day solar cell devices.

3.1.1 Operation

Silicon solar cells are made by selectively adding minute amounts of impurities to purified silicon. The addition of boron, for example, produces p-type silicon semi-conductor material having an excess of positive charges, while the addition of phosphorous produces n-type silicon with an excess of negative charges. In the fabrication of a solar cell the surface of a p-type silicon wafer is treated with an n-type dopant and followed by a high temperature diffusion process. The result is the formation of a very thin layer of n-type semiconductor material at the surface of the wafer. Between the n- and p-type material, the "p-n junction," a small region with fixed opposite charges, is formed, creating a potential barrier. Conditions are now right for this compound semiconductor to interact with light.

Light can be considered as consisting of tiny "packets" of energy (photons) having mass and traveling at extremely high speed. Alternatively, light may be described in terms of wave behavior. In this instance wave length is a measure of the energy content of the light; the shorter the wave length the higher the energy content, and vice versa. Figure 3.1-1 shows variations of terrestrial solar irradiance with wave length. The solar irradiance received at the earth above the atmosphere is about 1.36 kW/m^2, at the surface of the earth on a clear day with the sun directly overhead, the solar irradiance is about 1 kW/m^2.

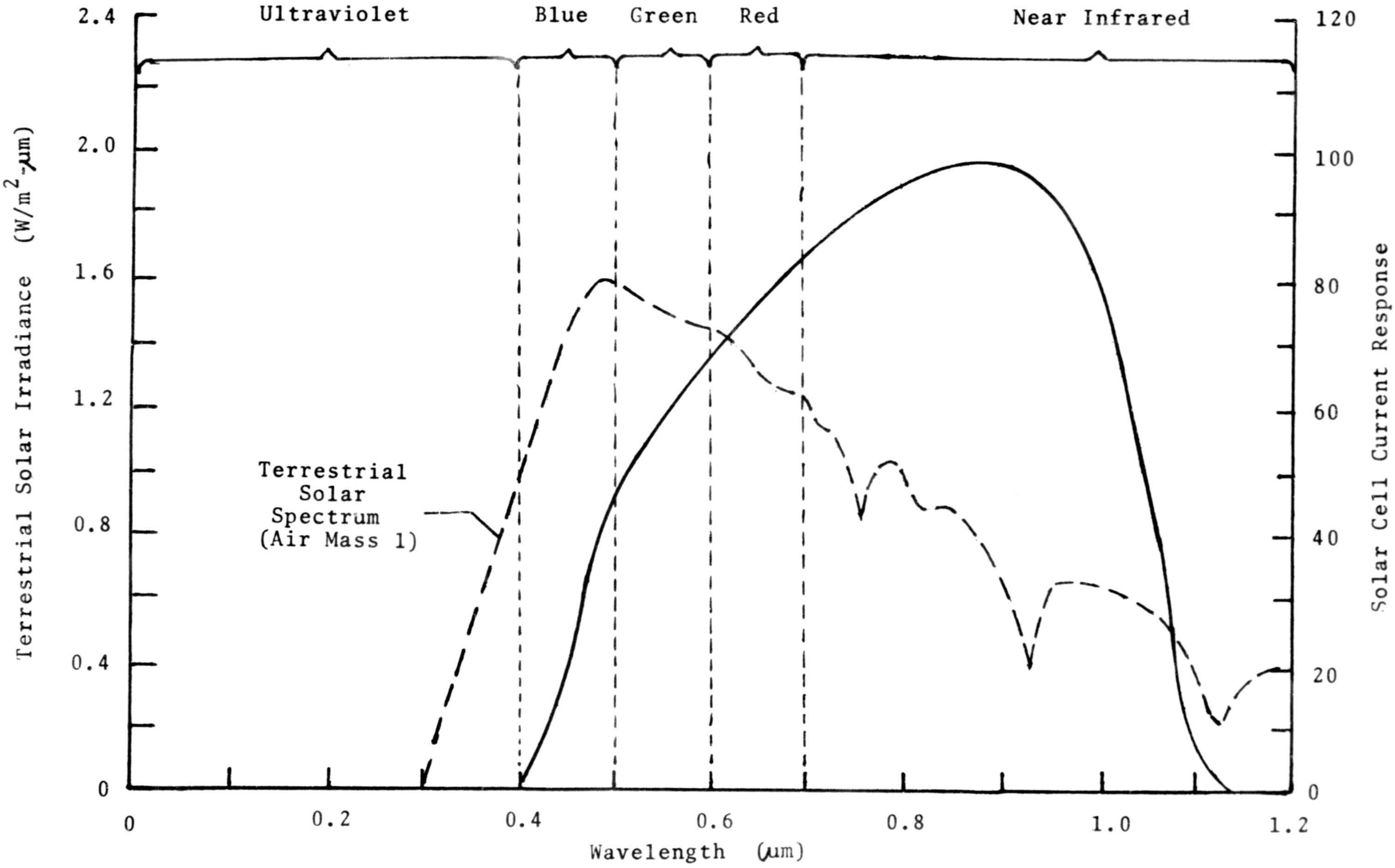

Figure 3.1-1 Silicon Solar Cell Spectral Response to the Terrestrial Solar Spectrum

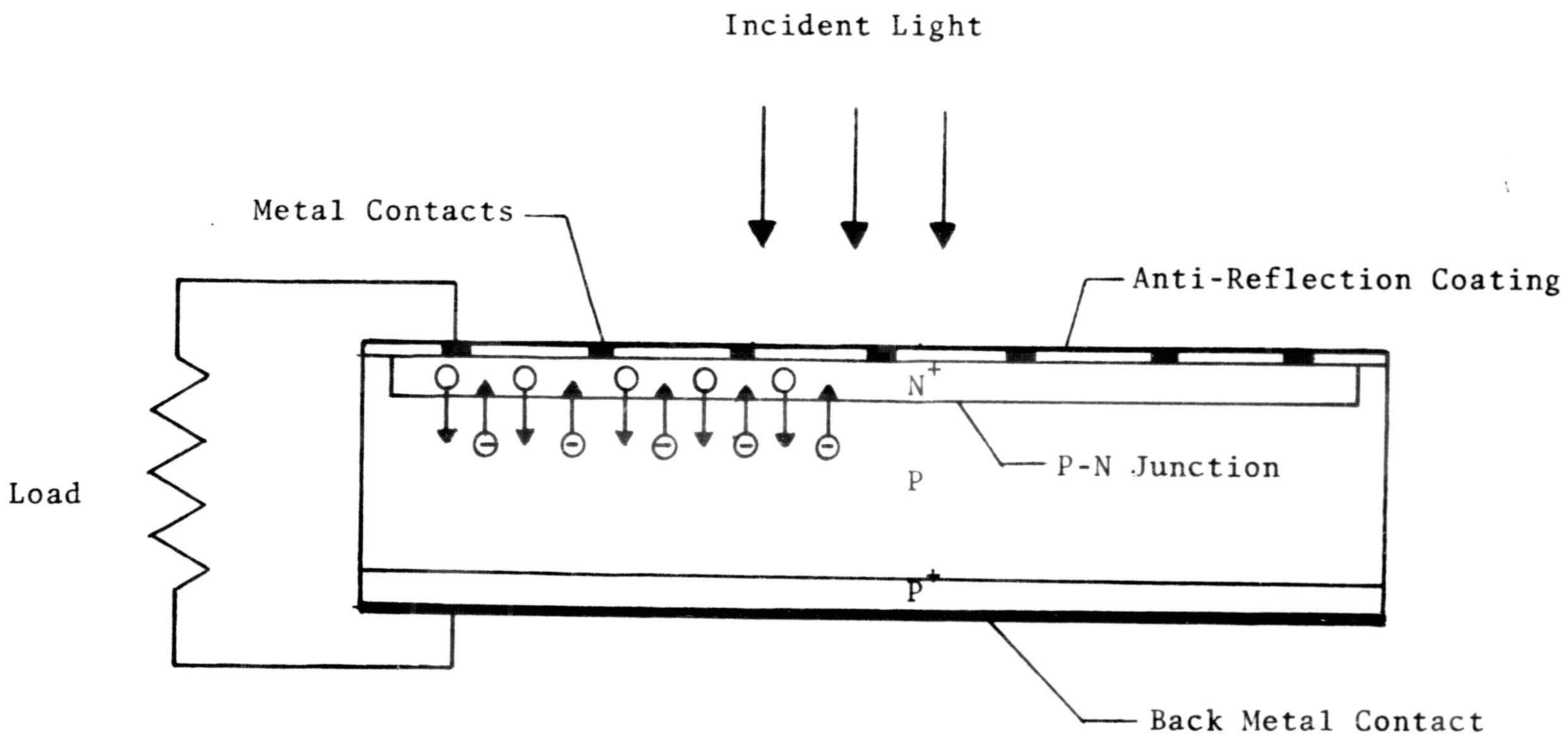

Figure 3.1-2 Model of Silicon Solar Cell Operation

When a photon of sufficient energy enters a solar cell it can interact with the atoms of the solar cell, creating an electron-hole pair, i.e., negative and positive charge carriers. These charge carriers are then free to move about in the cell. Negative carriers diffuse across the p-n junction into the n-type material; positive carriers diffuse into the p-type silicon. Both are prevented from flowing back across the junction by the potential barrier. Consequently there is a net build-up of charge resulting in the build-up of an electrical potential, i.e., voltage. By connecting leads to the bottom and the top of the cell, a circuit is formed, allowing current to flow through an external load (Fig. 3.1-2).

3.1.2 Efficiency

Almost all photons with energy greater than 1.1 electron volts, corresponding to a wave length of 1.15 μm, will be absorbed in the cell and create an electron-hole pair. The excess energy of any photon with energy greater than 1.1 ev is converted to heat in the cell. It can be seen in Fig. 3.1-1 that the region of silicon solar cell spectral response fits within the range of the terrestrial solar spectrum. Calculations indicate that at best a silicon solar cell can convert about 22 percent of terrestrial sunlight into electricity. Present commercial single crystal silicon solar cells for terrestrial use have efficiencies of 11 to 14 percent (at STC). The major causes and energy losses for such cells are displayed in the table below.

Energy Losses in a Practical Silicon
Solar Cell Under Terrestrial Sunlight (AM1)

Loss Due to:	Percent of Energy in Sunlight not Converted into Electricity
Low Energy Photons not Absorbed	23
Excess Photon Energy not Utilized	33
Internal Cell Functional Losses	29
Reflection, Series Resistance, Contacts	1.5
Total	86.5

Using as a guide the present production average efficiency of space-type silicon solar cells, it is presumed that terrestrial production-type cells could eventually reach about 17 percent efficiency.

3.1.3 Current-Voltage (i-V) Characteristics

The electrical characteristics of a PV cell can be understood from Figures 3.1-3 and 3.1-4. Illustrated in Fig. 3.1-3 is a simplified equivalent circuit which consists of, from left to right, a constant current generator, a non-linear junction (diode) impedance, and a load. Figure 3.1-4 shows the light and dark i-V response of a solar cell. When exposed to light a constant current i_{sc} is generated which causes a current, i_L, to flow in the load. A divergent current path through the non-linear junction supports current flow, i_J, given by the no-lignt curve. The magnitude of i_L, then, is the difference between i_{sc} and i_J.

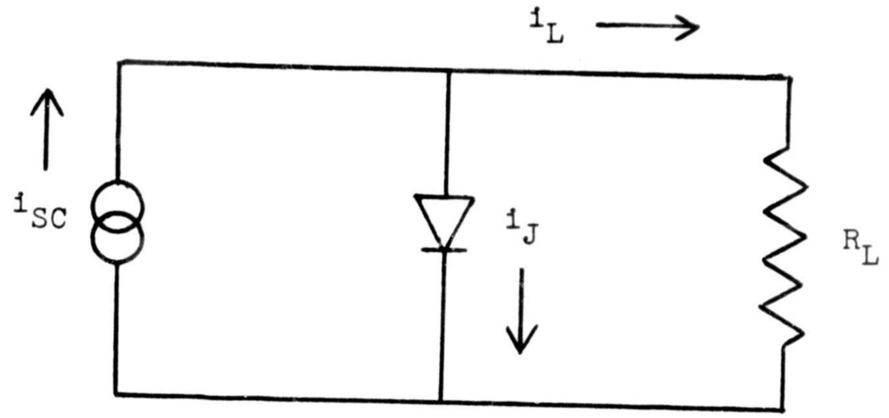

Figure 3.1-3 Simplified Equivalent Circuit of a Solar Cell

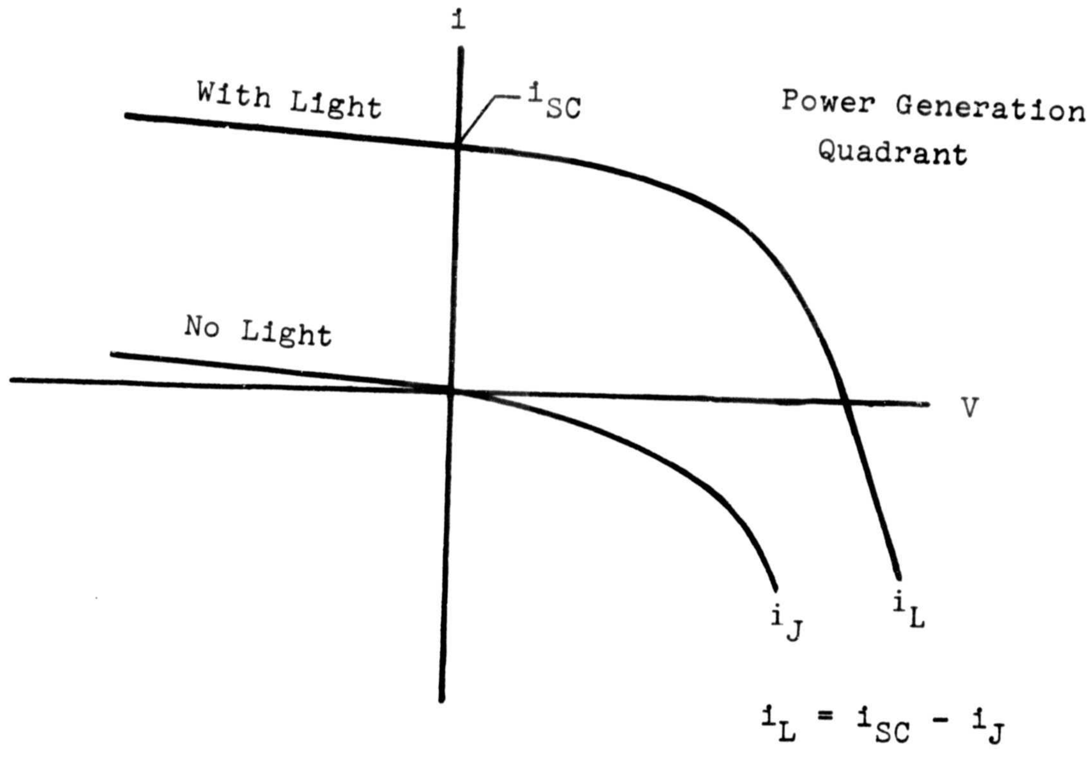

Figure 3.1-4 Effect of Light on Solar Cell Current-Voltage Characteristics

Two additional resistances must be recognized when considering actual cells, as compared to conceptual cells: (1) a shunt resistance due to "leakage" near the edge and corner of cells and (2) a series resistance due to the resistance of the cell material, the resistance encountered when electrons travel along the thin top sheet of n- or p-type doped material, and the contact resistance. Figure 3.1-5 shows the equivalent circuit modified to include these resistances, while fig. 3.1-6 displays the power generation i-V curve for a typical, present-day terrestrial silicon solar cell measured under a light intensity of 100 mW/cm^2 at 28°C.

At zero voltage, the current flow, i_J, through the junction is zero and $i_L = i_{sc}$. For small increases in voltage, i_J remains effectively zero and the slope of the i-V curve depends only on the cell shunt resistance. If R_{SH} were infinite, the curve would be horizontal in this region. At about 0.4 volts, however, the junction begins to conduct current, increasing exponentially with voltage, causing i_L to decrease rapidly. At V_{oc} (open-circuit voltage), i_J effectively equals i_{sc} and no current flows through the load. In the region, of the "knee" of the curve to V_{oc}, the slope of the i-V curve is governed by R_s; high values of R_s lead to steep slopes.

The power delivered to the load at any point on the i-V curve is the product of i and V at that point. Power output falls to zero at both V_{oc} and i_{sc} conditions; in between the power reaches a maximum, P_{max}, near the "knee" of the i-V curve. The ratio of P_{max} to the product of V_{oc} and i_{sc} is called the "fill factor" and is an important characteristic in evaluating cell performance. Values for i_{sc}, V_{oc}, i_{max}, V_{max}, P_{max}, fill factor (F.F.) and efficiency are listed in Fig. 3.1-6 for a typical commercial silicon solar cell.

Fig. 3.1-7 shows the effect of light irradiance on V_{oc} and i_{sc}. Short circuit current is directly proportional to irradiance. Open circuit voltage increases exponentially with irradiance at low intensities, rapidly reaching a saturation value. Thus over the irradiance range of practical

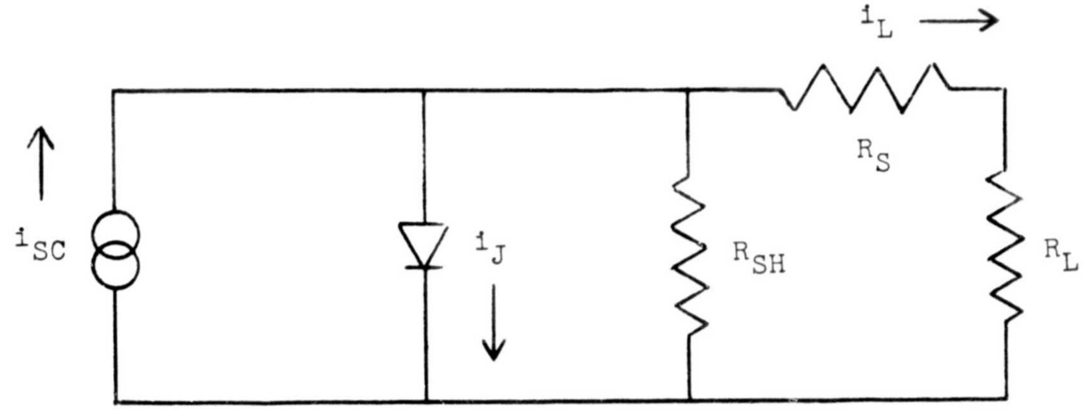

Figure 3.1-5 Equivalent Circuit of a Solar Cell Including Internal Series and Shunt Resistance

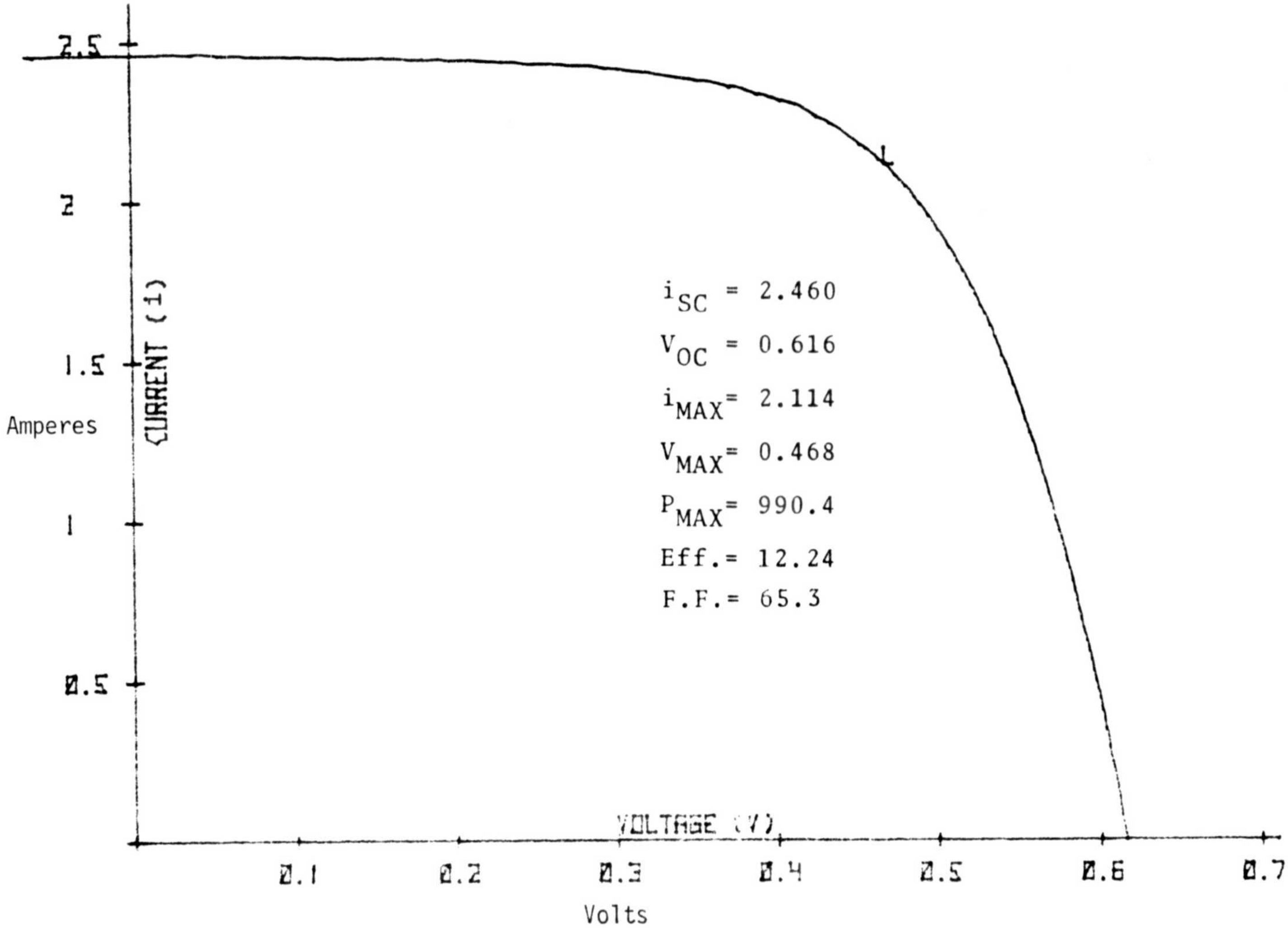

Figure 3.1-6 Current-Voltage Characteristics of a Typical Commercial Terrestrial Silicon Solar Cell of 80.9 cm^2 in Area at 28°C

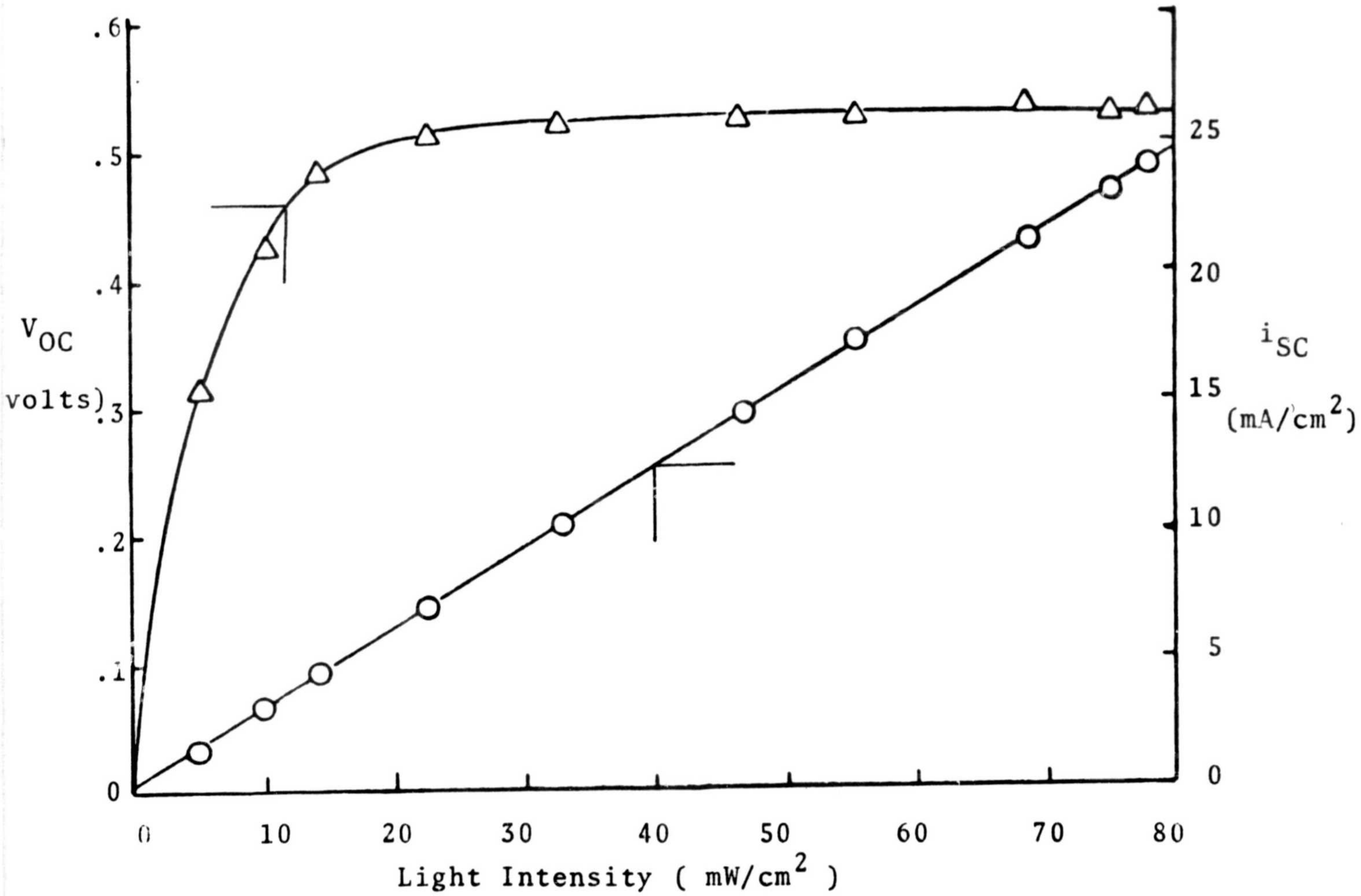

Figure 3.1-7 Dependence of Short Circuit Current and Open Circuit Voltage on Light Intensity

interest, V_{oc} is effectively constant. Figure 3.1-8 displays the i-V curves for a typical commercial cell at different light intensities. P_{max} at each irradiance value is indicated by a mark on the respective curve.

The effect of cell temperature on a typical commercial cell is shown in Fig. 3.2-9. Short circuit current is relatively insensitive to temperature, increasing less than 0.1 percent per °C. Open circuit voltage on the other hand shows a greater effect, decreasing 0.3 percent per °C. The temperature coefficient for P_{max} is about -0.3 percent per °C.

The effect of cell size or area on performance is apparent from the preceding presentation. Cell voltage is a function of cell material properties only and is independent of cell size. Solar cell current is a function of incident radiation and is directly proportional to illuminated surface area.

3.1.4 Manufacture

Solar cells are most commonly made from silicon. To start with, highly purified polycrystalline silicon with an addition of a p-type dopant, such as boron, is melted in a high temperature furnace that has a controlled atmosphere. Then, using a single crystal seed to initiate crystalization, a large, single crystal ingot is drawn from the melt in a carefully controlled manner. Finally, the ingot is trimmed, ground to a uniform diameter, and sliced into wafers 0.5 to 0.25 mm thick (Fig. 3.1-10). Recently, rectangular and square silicon sheet material, made by casting, edge film growth, or webdendrite growth techniques, has produced commercially. The reader is directed to Refs. 3-2 and 3-4 and the Bibliography for details of these processes.

The surface of a p-type wafer is (or sheet material) doped with an n-type dopant, such as phosphorous, in a high-temperature controlled diffusion process to create a very thin n-type layer and a p-n junction. To collect the generated current, metal contacts are applied to the front and back of the

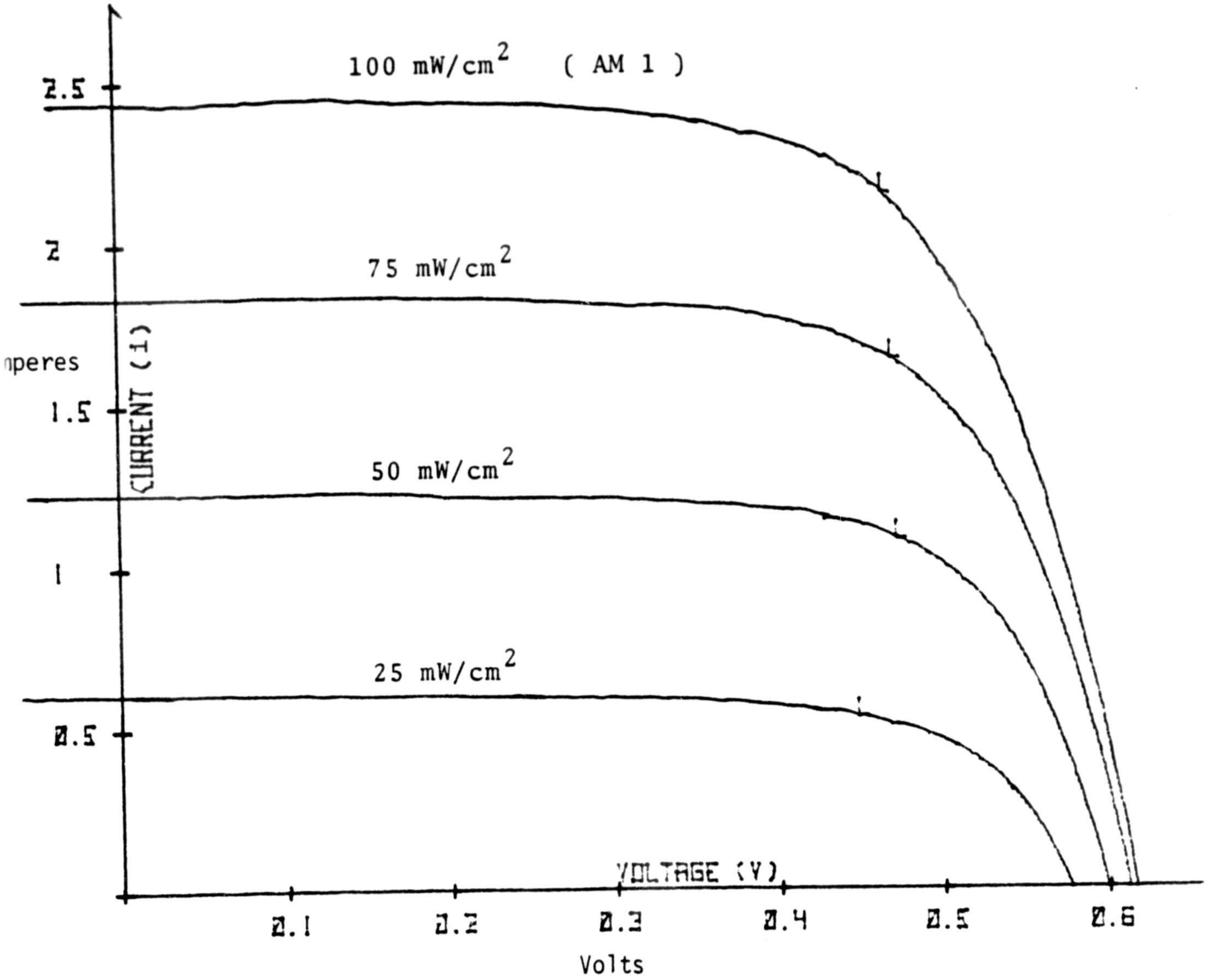

Figure 3.1-8 Current-Voltage Characteristics at Different Light Intensities for a Typical Commercial Terrestrial Silicon Solar Cell of 80.9 cm^2 in Area at 28°C

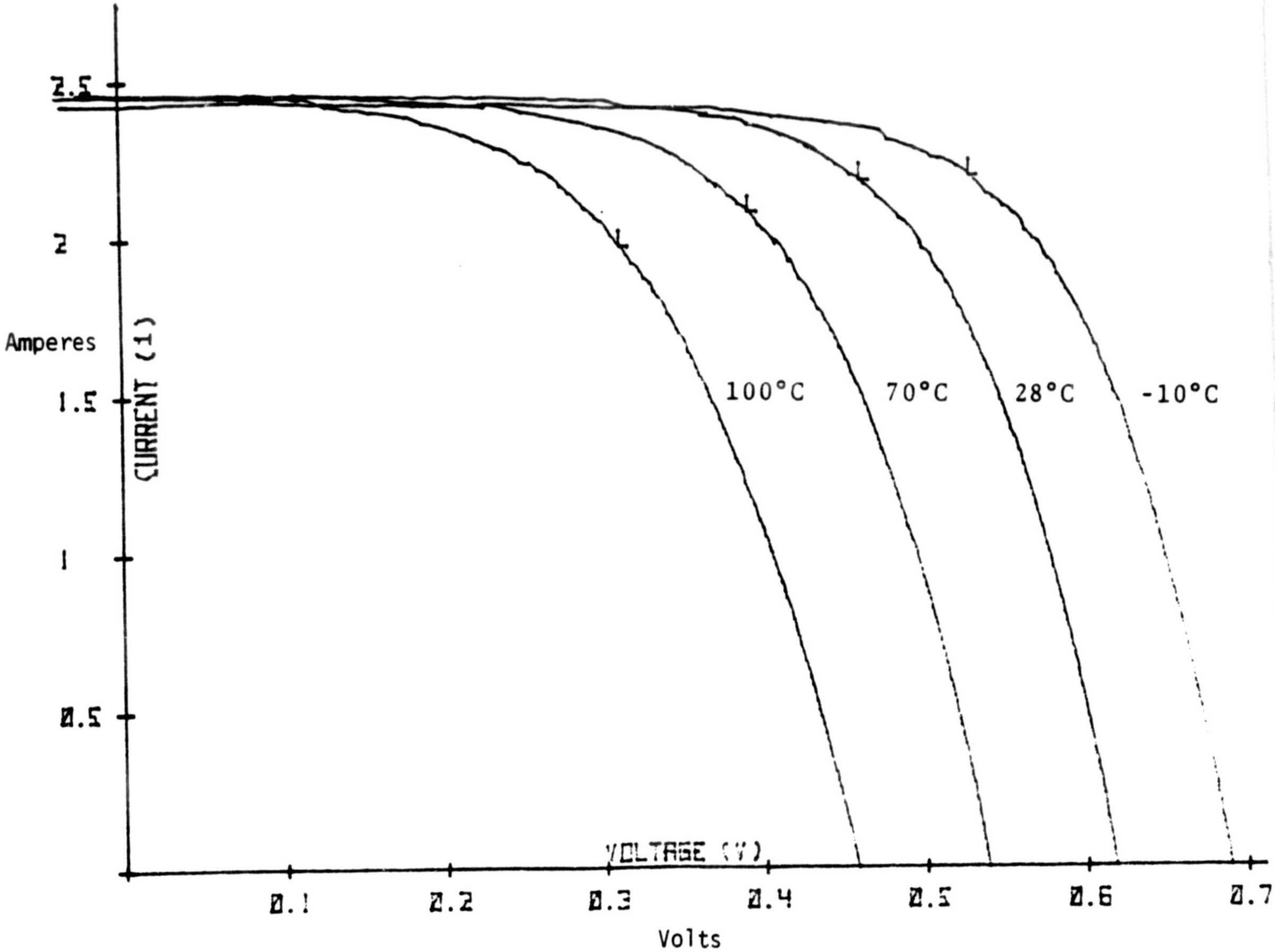

Figure 3.1-9 Current-Voltage Characteristics at Different Temperatures for a Typical Commercial Terrestrial Silicon Solar Cell of 80.9 cm^2 in Area at a Light Intensity of 100 mW/cm^2

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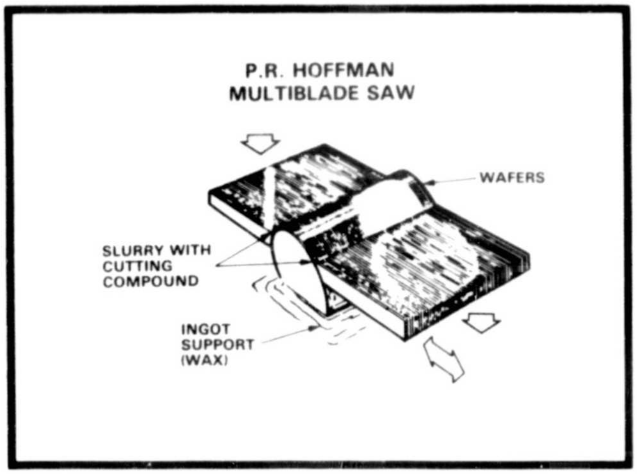
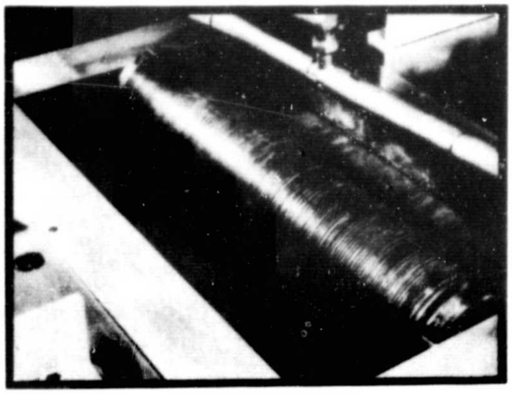
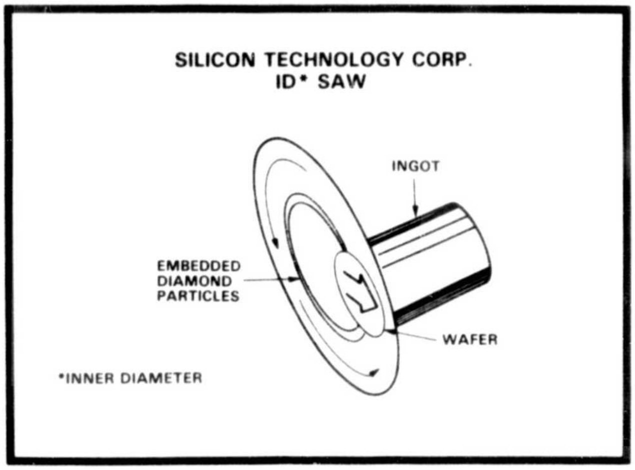






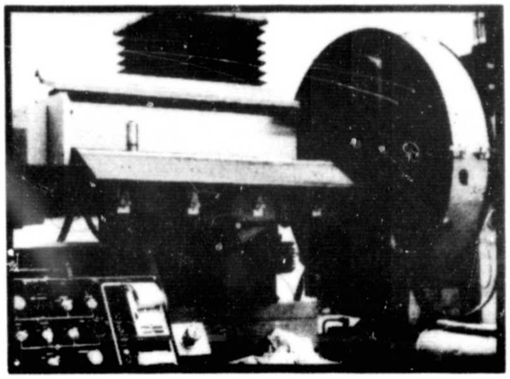


Figure 3.1-10 Two Methods Used for Slicing of Silicon Ingots (Source Ref. 3-4)

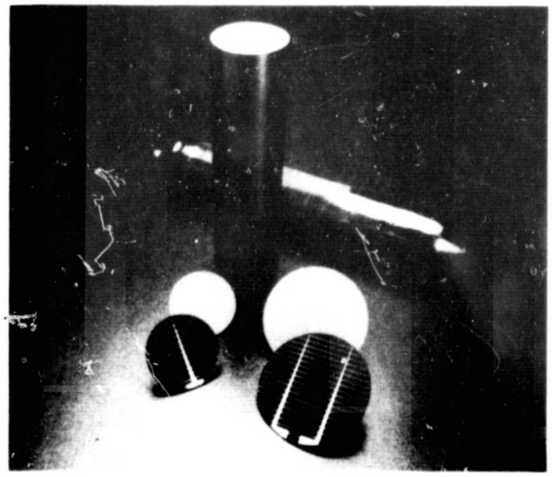


Figure 3.1-11 Silicon Ingots, Wafers, and Completed Cells (Source Ref. 3-4)

wafer (or sheet material). The front contact consists of a fine grid pattern that allows maximum light to enter the cell. The back of the cell is completely covered with contact material to achieve a low resistance ohmic contact. For increased efficiency, cells receive an anti-reflective surface coating.

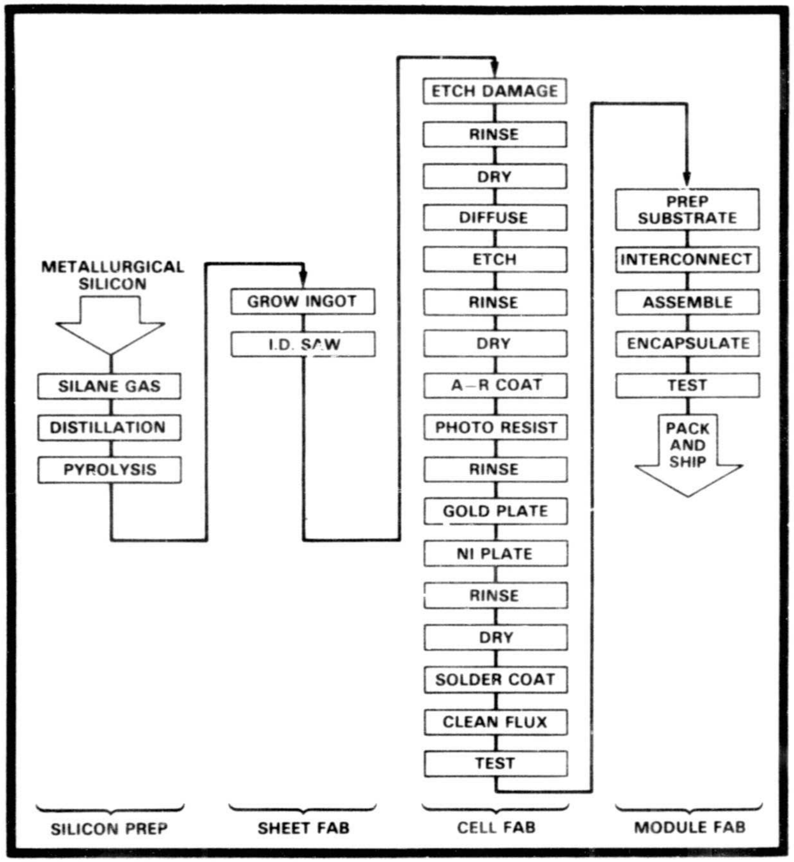
Fig. 3.1-11 shows, from back to front, a single crystal silicon ingot, a finished 2-inch diameter bar, and 2- and 3-inch diameter wafers and complete cells. A flow diagram of cell fabrication is presented in Fig. 3.1-12. Processing steps such as etching, rinsing, drying, etc., that were passed over in the brief description above are included in this more complete listing. Pictures of equipment used in cell fabrication are shown in Fig. 3.1-13.

Solar cell fabrication, as carried out at present, involves several batch-type process steps and can be characterized as relatively labor intensive. Over the last several years, many solar cell manufacturers have introduced mechanization and automation in some of the cell processing steps. With market growth to justify investment in capital equipment, the complete automation of solar cell production is foreseeable. In this regard advances in cell technology will also play an important role. A detailed discussion of this subject is beyond the scope of the present discussion. The reader is directed to Ref. 3-2 for the status of solar cell technology development funded by the U.S. DOE.

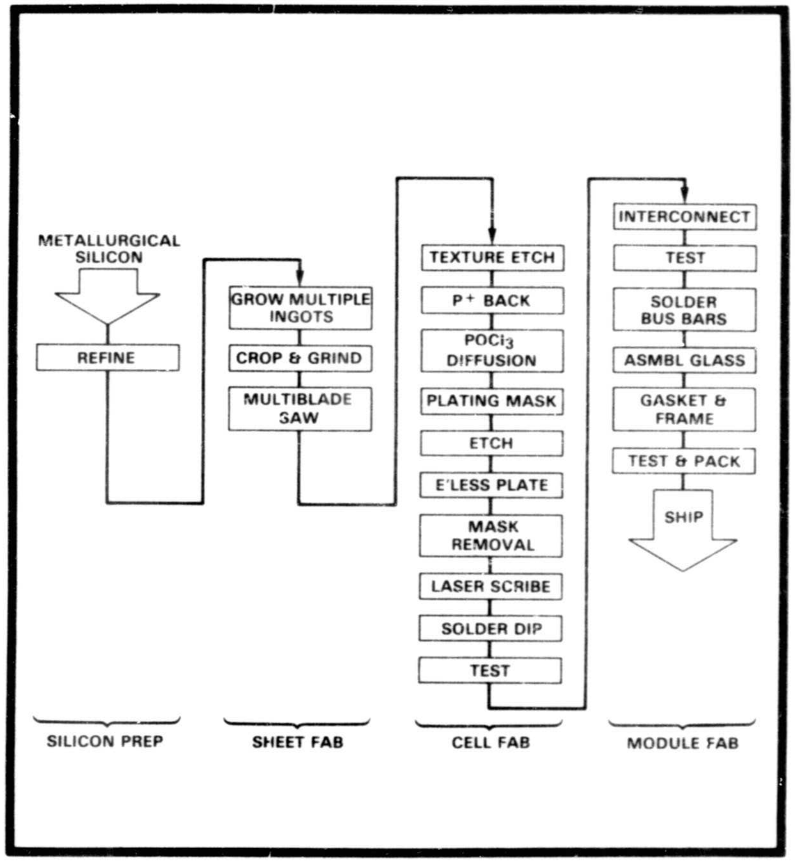
3.2 Modules, Panels, and Arrays

3.2.1 Definitions and Nomenclature

The Module, the basic building block of the system, consists of a number of solar cells electrically interconnected, and encapsulated within a supporting structure. To achieve the voltage and power levels desired, individual solar cells are combined in series and parallel arrangements, analogous to storage battery cells. According to electrical circuit principles, voltages in series add, and in parallel are equivalent to the



Typical 1977 Sequence



Anticipated Sequence in Near-Term

Figure 3.1-12 Cell and Module Fabrication Flow Diagram
(Source: Ref. 3-4)

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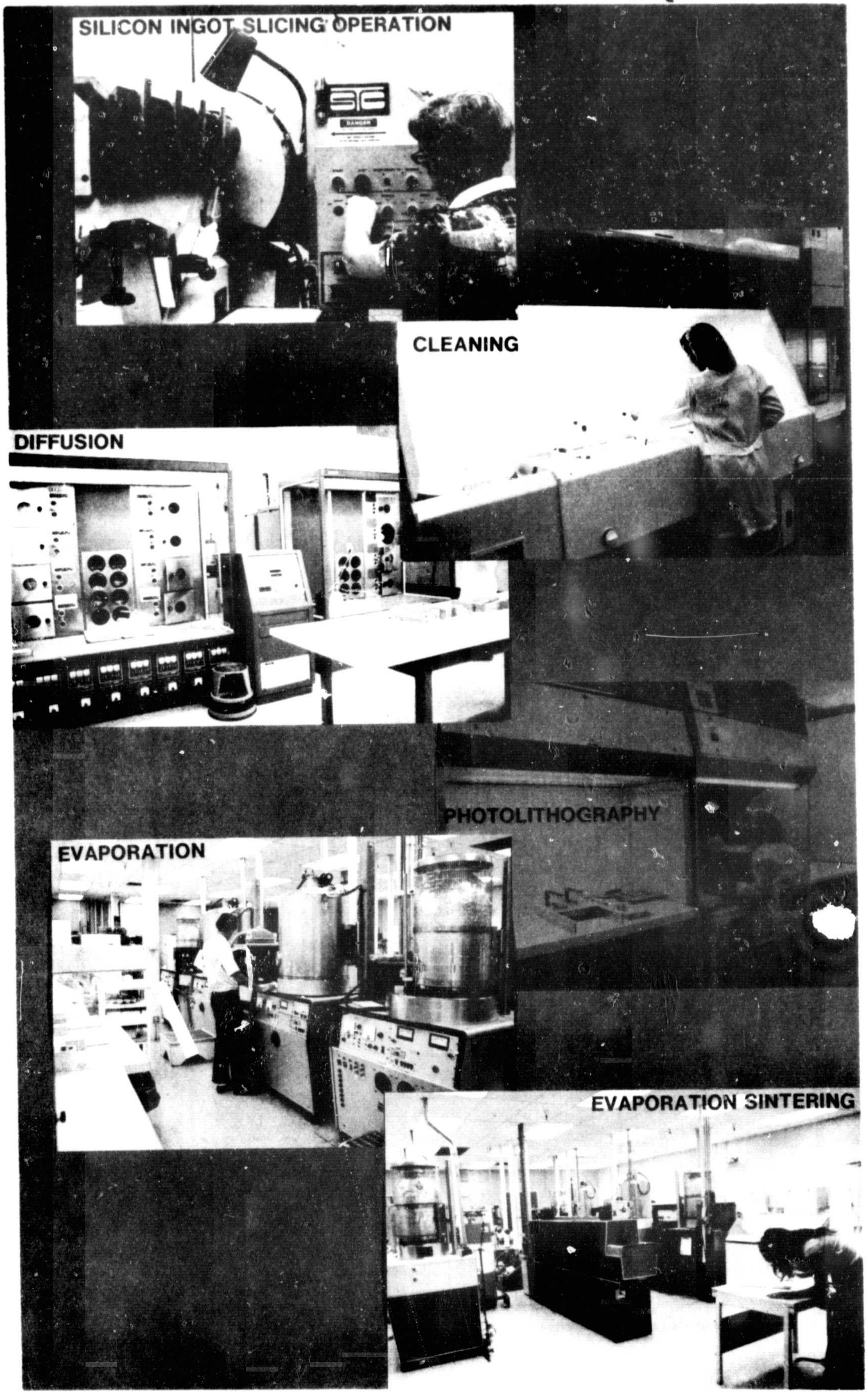


Figure 3.1-13 Equipment Used in Solar Cell Fabrication (Source: Ref. 3-1)

value of the lowest voltage. Likewise, currents in parallel add, while those in series are equivalent to the lowest current produced (Fig. 3.2-1).

Within a module, the cell arrangement may consist of either one string of series-connected cells or two or more series-strings of cells connected in parallel (Fig. 3.2-2). Modules are electrically connected (in series and parallel) and physically grouped into panels. Panels are grouped into an electrically connected and mechanically integrated assembly to form an array that provides the desired system output power and voltage (Fig. 3.2-3).

The nomenclature for the electrical circuits associated with the array is shown in Fig. 3.2-4. Groups of cells arrayed in series are called substrings; substrings arrayed in parallel are called series blocks; series blocks connected in series are called branch circuits; and branch circuits are connected in parallel to form the array circuit.

3.2.2 Module Efficiency

The current-voltage characteristics of a module are the combined characteristics of the several cells that are connected in series or parallel. Fig. 3.2-5 shows representative i-V curves for a commercial module with 38-10cm diameter cells connected in series. At 28° C and 1 kW/m^2 irradiance the P_{max} (or "peak power"*, found on the manufacturer's data sheet), is 35W.

Module efficiency (η_M) at a given cell temperature, T, is the module maximum power divided by the gross module area and solar irradiance.

$$\eta_M \langle T \rangle = \frac{\text{max. power, W}}{\text{gross area, m}^2 \times \text{solar irradiance, W/m}^2}$$

---

*The use of the term peak power (expressed in units of peak watts, W_p) and its usage in characterizing system power output or power cost ($\$/W_p$) may confuse and mislead more than help. Peak power is associated with a single set of conditions, namely, 28° C and 1 kW/m^2 irradiance. In practice, module operating temperature is usually significantly higher than 28° C. and actual solar irradiance varies greatly from 1 kW/m^2, both daily and seasonally.

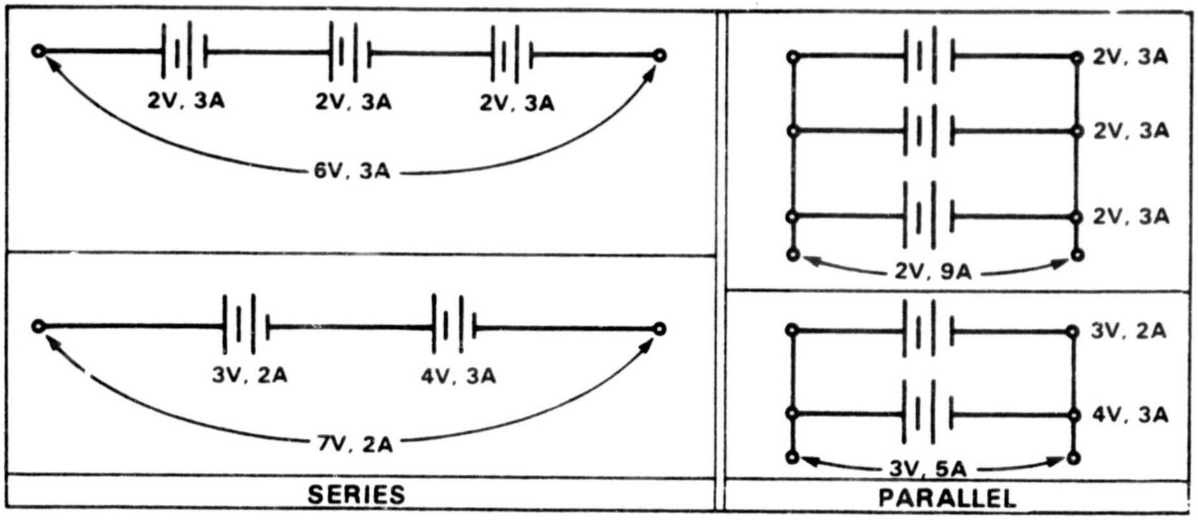
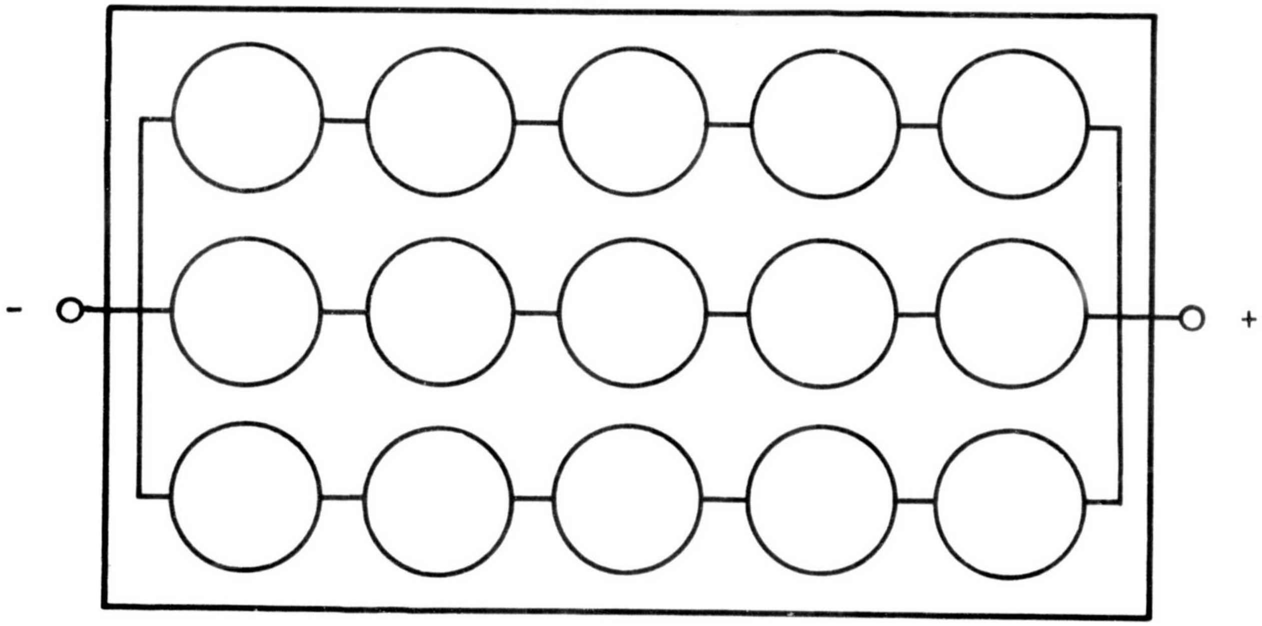


Figure 3.2-1 Basic Series-Parallel Relationships (Source: Ref. 3-10)



Conditions at P_{MAX}

Each Cell:	0.45V, 1.5A
Each Series String:	2.25V, 1.5A
Module:	2.25V, 4.5A

Figure 3.2-2 Series-Parallel Cell Connections in a Module

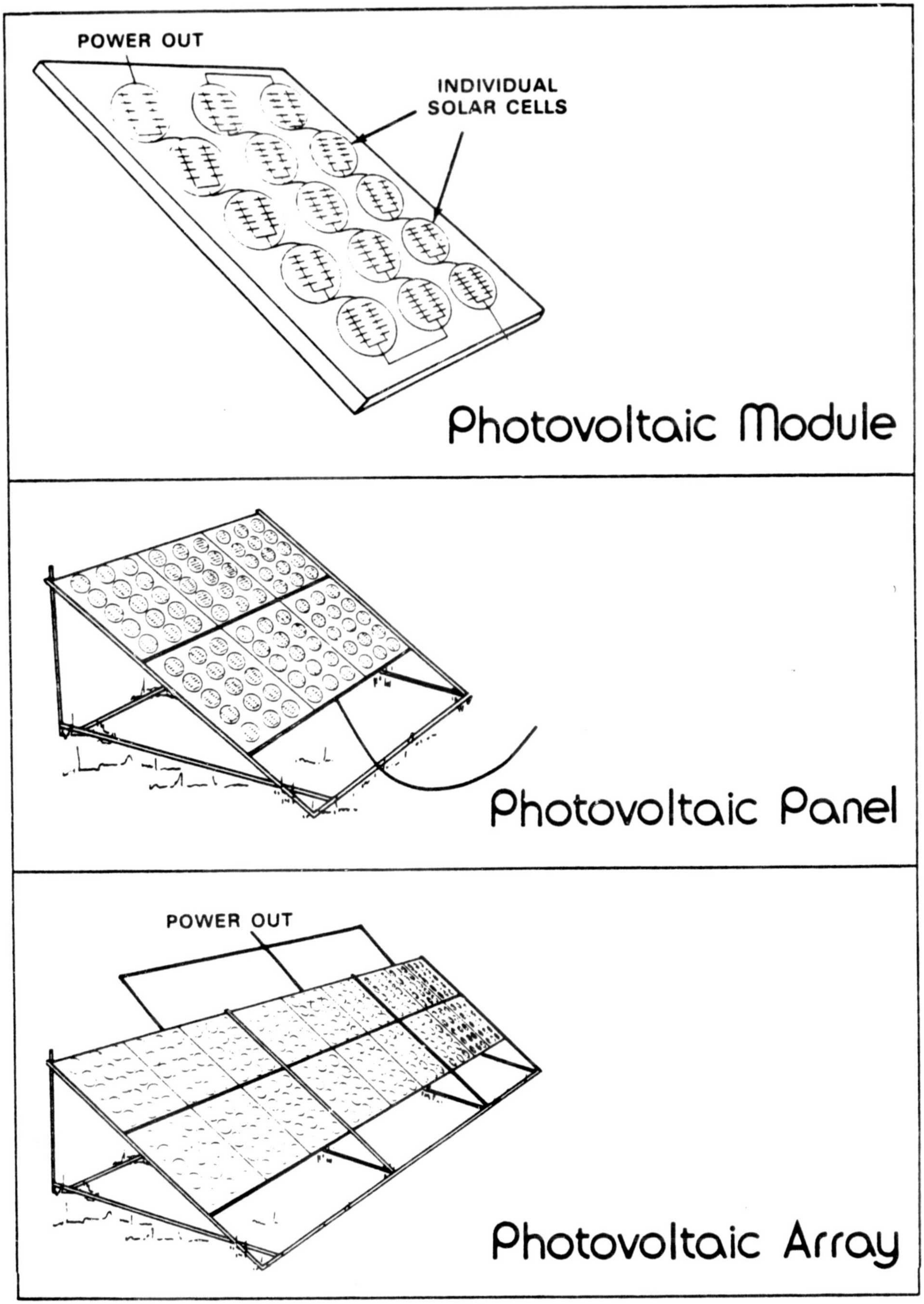


Figure 3.2-3 Solar Cell Array Components (Source Ref. 3-10)

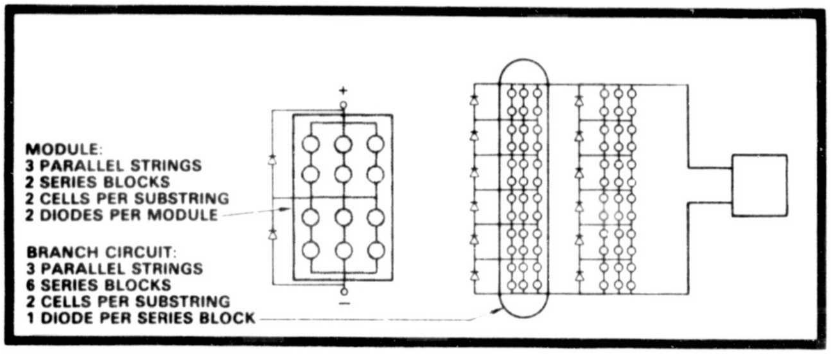


Figure 3.2-4 Series/Parallel Nomenclature
(Source: Ref. 3-4)

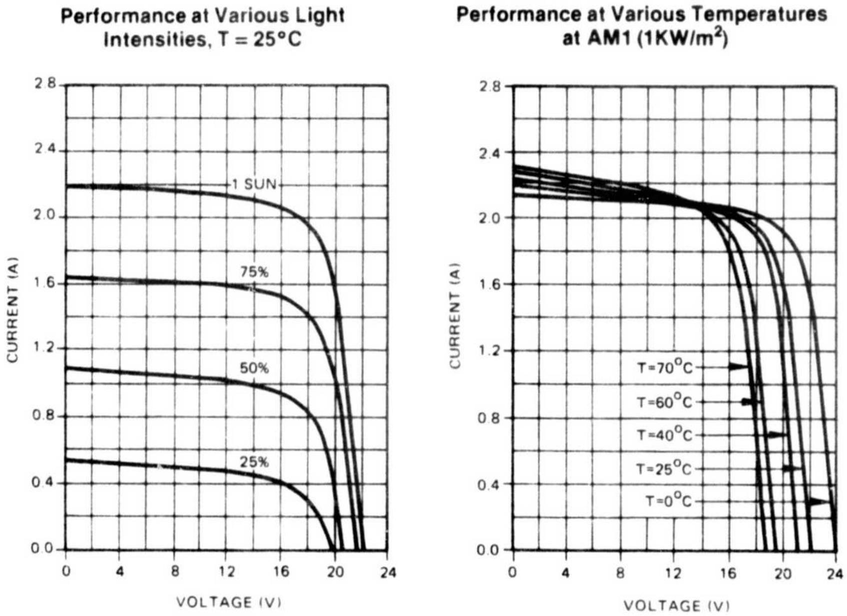


Figure 3.2-5 Representative Module Current-Voltage Characteristics
(Source: Solarex Corp., Data Sheet 6022-1 June 1981)

The gross area of the commercial module discussed above is 0.50 m^2. Therefore the efficiency of this module at standard test conditions (STC) of 28° C. and 1 kW/m^2, is

$$\eta_M \langle STC \rangle = \frac{35\ W}{0.50\ m^2 \times 1000\ W/m^2} = 0.07$$

At a higher temperature, as most likely would be experienced in actual operation, module efficiency decreases. Typically the P_{max} temperature coefficient, P_{TC}, is about -0.003 W/W/°C. Module efficiency and P_{max} at cell operating temperature, T_{op}, and 1 kW/m^2 can be found from the following equations:

$$\eta_M \langle T_{op} \rangle = \eta_M \langle STC \rangle \left[1 + P_{TC} (T_{op} - 28)\right]; \text{ and}$$

$$P_{max} \langle T_{op} \rangle = P_{max} \langle STC \rangle \left[1 + P_{TC} (T_{op} - 28)\right]$$

Given the relatively high day time ambient temperature experienced in countries which lie between 30° N and 30° S latitudes, module temperature for 1 kW/m^2 irradiation will probably be between 50° and 65° C. Module efficiency and P_{max} for the commercial module discussed above would be, for example, at 55° C,

$$\eta_M \langle 55° \rangle = 0.07 \ [1 - 0.003\ (55\text{-}28)] = .064$$

$$P_{max} \langle 55° \rangle = 35 \ [1 - 0.003\ (55\text{-}28)] = 32\ W$$

At present commercial module efficiencies range from about 7 to 12 percent at STC. To understand why module efficiency runs considerably below terrestrial bare cell efficiency (11-14 percent at STC), it is necessary to examine briefly the main factors contributing to loss of efficiency. Module efficiency may be treated as the product of three major efficiency terms (Ref. 3-3):

$$\eta_M \langle T_{op} \rangle = \eta_{TO} \times \eta_{EC} \times \eta_p \quad , \text{ where}$$

$\eta_{TO} = 1 + P_{TC} (T_{op} - 28)$,
η_{EC} = encapsulated cell efficiency at STC, and
η_p = module packing efficiency

Encapsulated cell efficiency is the bare cell efficiency less certain losses: (1) electrical mismatch of the cells; (2) I^2 R losses in the cell interconnects and module buses and leads; and (3) optical transmission losses through the encapsulant and cover materials. Typically η_{EC} may range from 0.10–0.13.

Module packing efficiency is determined by several factors. Chief among these is the shape and size of the cells and how closely they may be fitted together in the module. Square or rectangular cells may be assembled so that there is little wasted space between cells. This is not the case with circular cells. Two other factors influence η_p, namely, the amount of module border or frame area and the amount of bus and interconnect area. Typically η_p ranges from 0.6–0.7 for circular cells and 0.8–0.9 for squared-off cells.

3.2.3 Module Operational Losses

Array power losses, when observed during system operation, can be of a permanent, extended, or temporary nature.

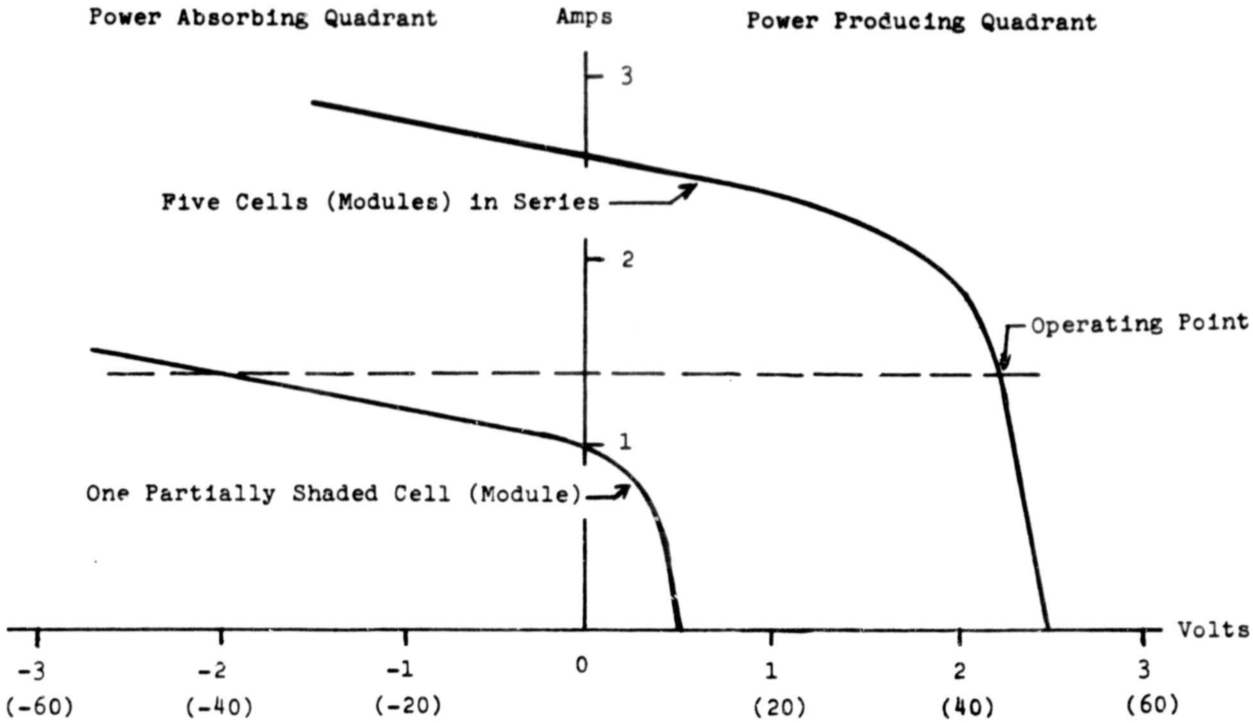
(1) <u>Permanent losses</u>. These result from external damage, e.g., hail and vandalism, or from internal causes such as poor electrical matching of cells or modules and cell interconnect failures. The effect of cracked cells and electrical mismatch is discussed below. Cell interconnect failure usually results from poorly designed interconnects and thermal mismatch of materials.

(2) Extended losses. These are mainly caused by dirt accumulation on the surface of the modules which reduces the transmission of light to the cells. Depending on the type of cover material, most of this loss is recoverable upon washing the surface of the module. Permanent power loss with glass covers is negligable. Depending on the environment, plastic cover materials such as silicone rubber may experience 10 to 20 percent permanent (non-recoverable on washing) loss. This loss is the result of darkening of the silicone rubber due to ulltraviolet degradation and particles of dirt embedded in its soft surface.

(3) Temporary losses. These are due mainly to shading of sections of a module, panel, or array by trees, buildings, local physical features, or other obstructions. The loss depends on the area shadowed, the magnitude of the reverse-bias effect, and the particulars of the series-parallel circuit arrangements. When the shadowing ceases, full power is regained.

(4) Reverse-bias effects. These occur when the current-producing capability of a cell, module, or panel is significantly less than that of others in its series string. Such a condition can occur when the cell, module, or panel is shadowed, cracked, or otherwise degraded or when it is poorly matched electrically with others in its string. An illustration of the reverse-bias effect is given in Fig. 3.2-6 for a series string of 6 cells or modules, the last partially shaded. At the selected operating point, the first 5 cells produce 1.4A at 2.25V (3.15W). At a current of 1.4A, the shaded cell is operating in the power absorbing quadrant at -2V and is dissipating 2.80W. The net power produced by the series string is 3.15-2.80 = 0.35W. At a slightly higher operating point, all of the power generated would be dissipated in the shaded cell. A comparable situation would obtain for a panel consisting of 6 modules connected in a series string (Fig. 3.2-6).

Operating a string in this fashion is extremely inefficient but the dissipation of a few watts usually makes little difference. If, however, more cells or modules are connected in series, the power that can be dissipated in one cell or module increases and so does the possibility of excessive heating and permanent damage. Experience indicates that for panels operating above 40-50V, damage may be incurred unless proper precautions are taken.



	At Operating Point
Five Cells:	1.4A, 2.25V, 3.15W
Shaded Cell:	1.4A,-2.0V, 2.80W
Five Modules	1.4A, 45V, 63W
Shaded Module:	1.4A,-40V, 56W

Figure 3.2-6 Current-Voltage Characteristics of Series String of Six Illuminated Cells (or Modules) with the Last Partially Shade

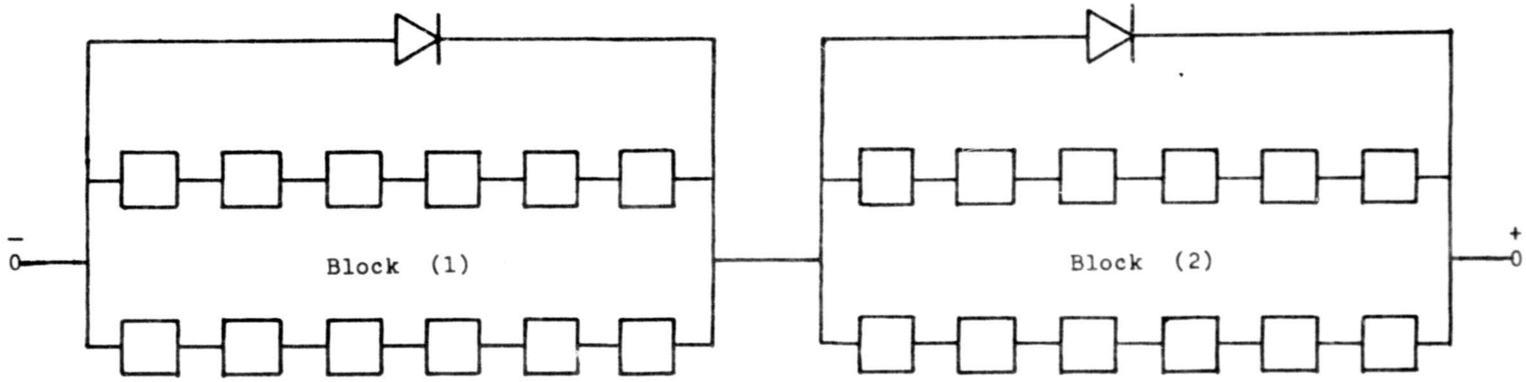
Well-designed modules, panels, and arrays incorporate devices and design features which limit power loss and prevent damage due to reverse-bias operation. The chief approaches used are(1) electrical matching of cells in modules and of modules in panels,(2) provision for multiple current paths in the module or panel wiring circuits, and(3) the use of bypass diodes to limit maximum reverse current.

The use of a protective bypass diode is illustrated in Fig. 3.2-7. In normal operation the current flows through the cells, modules, or panels only because the diode is connected in reverse. If a cell, module, or panel is reverse-biased so that sufficient reverse voltage develops in the protected segment, the diode becomes forward-biased and conducts current, thereby prohibiting development of high reverse voltage in the protected segment.

3.2.4 Design, Fabrication and Manufacture

(1) Modules. Most early commercial modules were constructed with the solar cells embedded in a clear silicone rubber encapsulant and a substrate supporting element of aluminum or fiber-reinforced plastic. More recently, many commercial modules are of a glass and plastic laminate design (Fig. 3.2-8). A summary of the status of various materials used in module fabrication is provided in Fig. 3.2-9; a photograph of assorted modules produced by U.S. manufactures is shown in Fig. 3.2-10.

The proprietary development of processes and equipment for the automated assembly of modules has been actively pursued by several manufacturers. Additionally, government funding for module assembly development has been allocated in the U.S. through the DOE's Low Cost Solar Array Project, and in Japan through the Ministry of International Trade and Industry's New Energy Development Organization. The status of the DOE's program, as of July 1981, is summarized in Fig. 3.2-11.



	(a)	(b)	(c)
When —□— Represents:	Cell	Module	Panel
Then Block (1) and (2) Represent:	Modules	Panels	Array

Figure 3.2-7 Use of By-Pass Diodes to Protect from Reverse-Bias Effects

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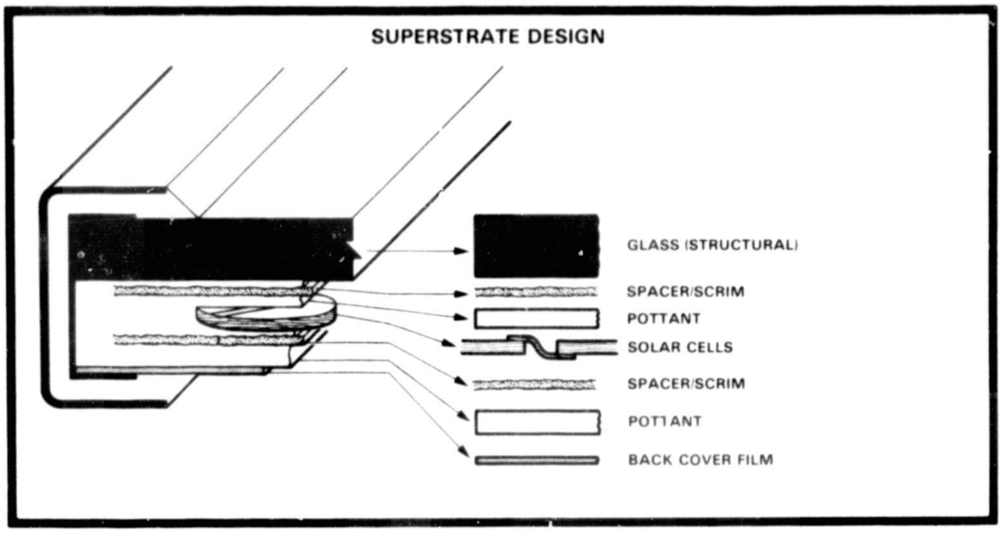

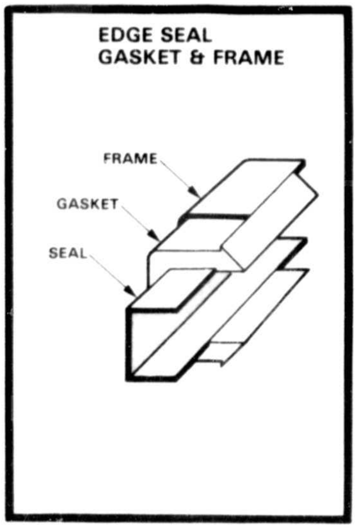

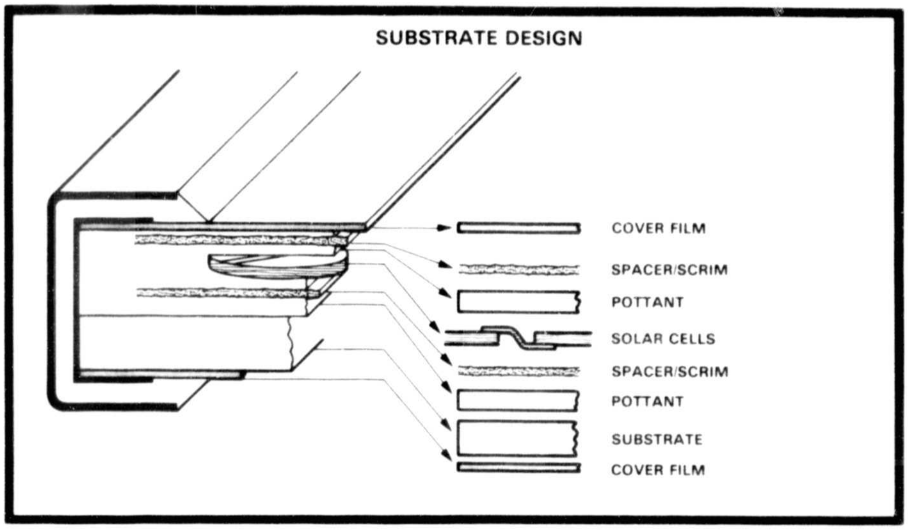

Figure 3.2-8 Typical Contemporary Module Designs (Source Ref. 3-4)

MODULE ELEMENT	MATERIAL	STATUS	NOTES
SUPERSTRATE (STRUCTURAL)	GLASS — LOW IRON TEMPERED (SUNADEX)	•	STRONGEST, BUT DEFECT SENSITIVE
	— LOW IRON ANNEALED	•	THICKNESS DETERMINED BY HAIL OR WIND
	— BOROSILICATE	••	HIGHER COST THAN SODA LIME
	ACRYLIC SHEET — (PLEXIGLAS, LUCITE)	•	SUBJECT TO THERMAL STRESS FAILURES
	POLYCARBONATE (LEXAN)	••	TOUGH AND HIGH COST
PLASTIC FILMS (UV SCREEN)	FLUOROCARBON — (TEDLAR)	•	DuPONT UV SCREENINF FILM
	ACRYLIC — (KORAD)	•	XCEL UV SCREENING FILM
	(PMMA)	••	3M UV SCREENING FILM
	POLYESTER — (LLUMAR)	••	MARTIN UV SCREENING FILM
SURFACE TREATMENTS	ABRASION RESISTANT HARD COATS	••	WEATHERING LIFE NOT DETERMINED
	ANTI-REFLECTION TREATMENT FOR GLASS	•••	ACID ETCH OR SILICATE CONVERSION
	ANTI-SOILING TREATMENTS OR WASHES	•••	BEING DEVELOPED
POTTANT/ADHESIVE	SILICONE RUBBER (RTV 615, SYLGARD)	•	HIGH COST CASTING LIQUID
	SILICONE RUBBER (G.E. 534-044)	••	LOWER COST CASTING OR SPRAY LIQUID
	SILICONE GEL (DOW)	•	USED IN FILLING FIXED CAVITY DESIGN
	POLYVINYL BUTYRAL (PVB SAFLEX)	•	THERMOPLASTIC IN SAFETY GLASS LAMINATION
	ETHYLENE VINYL ACETATE (EVA)	•••	MELTS AND CURES DURING LAMINATION
	ETHYLENE METHYL ACRYLATE (EMA)	•••	SOFTENS AND CURES DURING LAMINATION
	POLY-N-BUTYL ACRYLATE (PNBA)	•••	CASTING SYRUP CURES IN PLACE
	ACRYLIC LAMINATING SHEET (3M)	••	TO BE EVALUATED
	ALIPHATIC POLYETHER URETHANE	••	TWO PART CURING SYRUP FOR CASTING
SPACER	NON-WOVEN GLASS MAT (CRANEGLAS)	••	FOR AIR RELEASE AND ELECTRICAL ISOLATION SPACING
SUBSTRATE (STRUCTURAL)	GLASS, TEMPERED OR ANNEALED	•	DIELECTRIC AND THERMAL MATCH
	PORCELAINIZED STEEL	••	SUBJECT TO WARP AND CRACK SENSITIVE
	GLASS FIBER REINFORCED POLYESTER	•	POTTANT BOND DELAMINATION PROBLEM
	ALUMINUM (SHEET AND EXTRUSIONS)	•	COST AND THERMAL EXPANSION DISADVANTAGES
	GLASS REINFORCED EPOXY (NEMA G10)	•	CIRCUIT BOARD SUBSTRATE
	WOOD FIBER HARDBOARD	••	LOWEST COST STRUCTURAL MATERIAL
	MILD STEEL (COATED FOR CORROSION)	•••	LOWEST COST METAL
	GLASS-REINFORCED CONCRETE	••	POTENTIAL FOR INTEGRATED ARRAY STRUCTURE
BACK COVER	POLYESTER FILM — (MYLAR)	•	DIELECTRIC FILM
	FLUOROCARBON, PIGMENTED (TEDLAR)	••	DIELECTRIC FILM
	ALUMINUM FOIL/POLYMER LAMINATES	••	PROVIDES HERMETICITY AND DIELECTRIC
	STEEL FOIL/POLYMER LAMINATES	••	BETTER THERMAL EXPANSION MATCH THAN Al
	POLYESTER FILM (SCOTCHPAR 20CP WHITE)	••	SIMILAR TO MYLAP
	ACRYLIC FILM — (WHITE KORAD)	••	DIELECTRIC FILM
	WHITE POLYETHYLENE	••	DIELECTRIC FILM
	COATINGS FOR MILD STEEL	•••	BOTH COATINGS AND ADHESIVE FILMS
	COATINGS FOR WOOD HARDBOARD	•••	TO REDUCE HYDROTHERMAL RESPONSE

* USED IN CURRENT PV MODULES
** COMMERCIAL MATERIAL BEING EVALUATED FOR PV MODULES
*** MATERIAL UNDER DEVELOPMENT AND EVALUATION FOR PV

• 0.001 in. = 0.025 mm; 0.040 in. = 1.0 mm

Figure 3.2-9 Module Material Status; U.S.DOE Low-Cost Solar Array Project July 1981 (Source: Ref. 3-4)

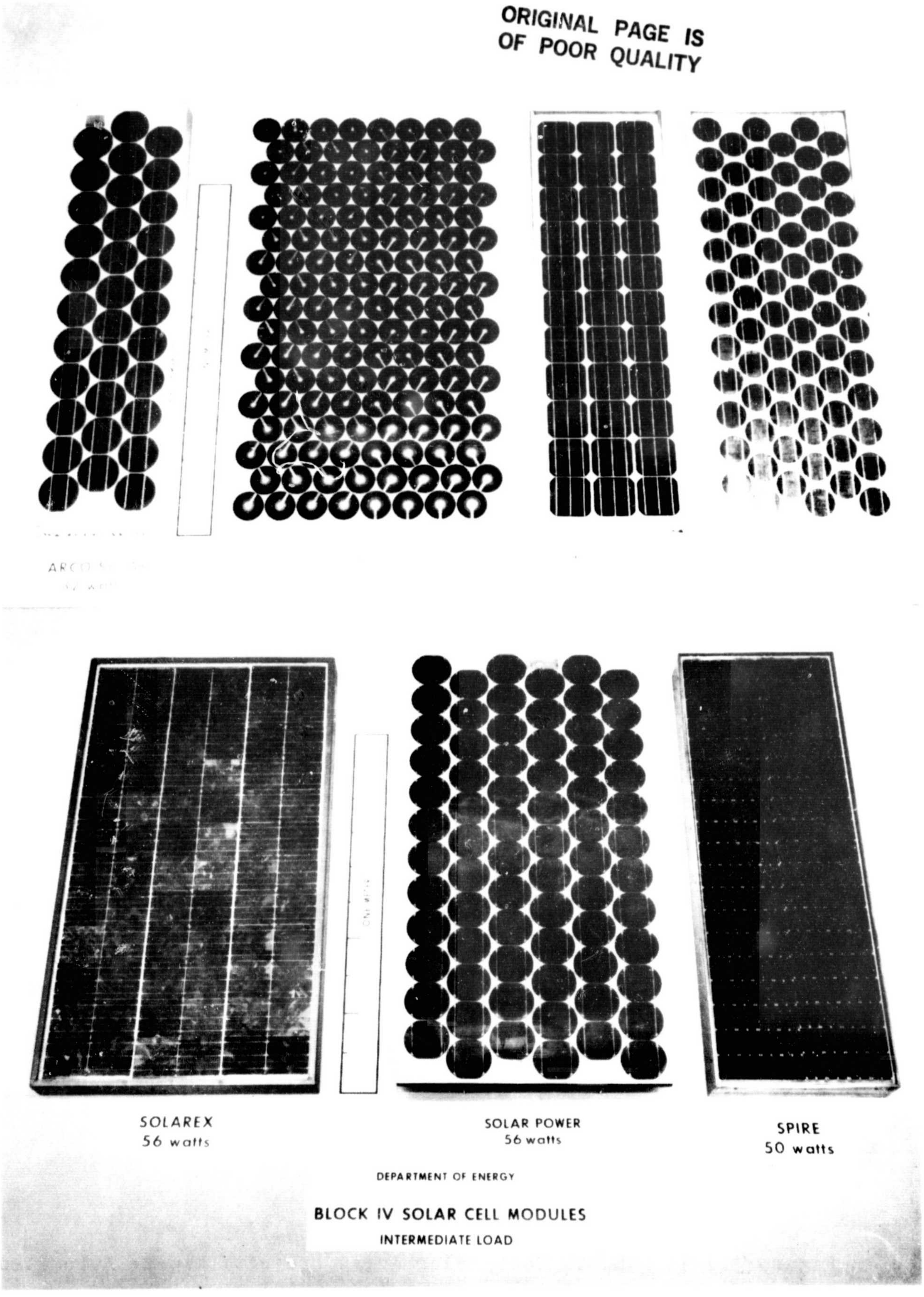

Figure 3.2-10 Selected Modules Produced by U.S. Manufacturers

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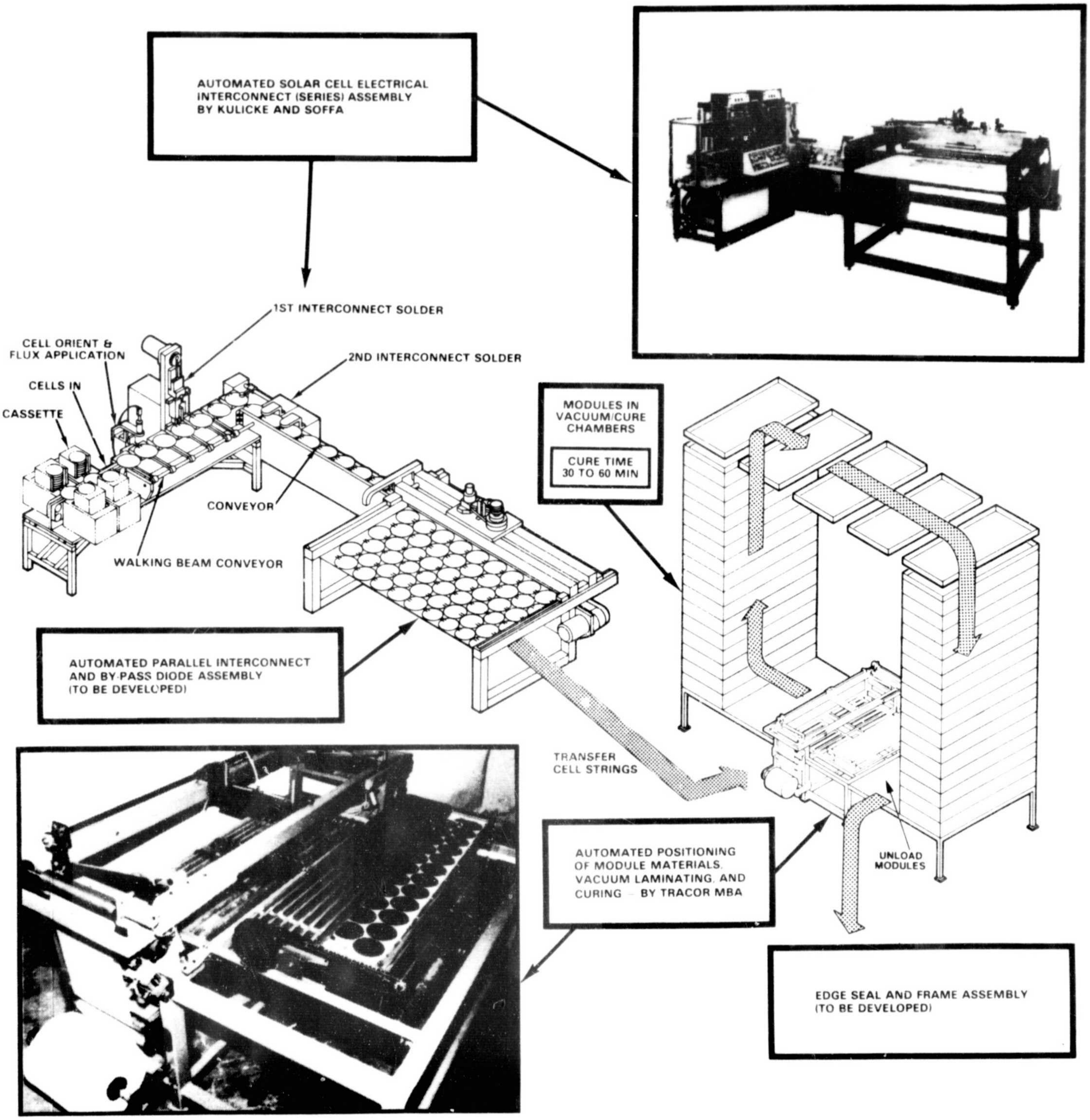

Figure 3.2-11 DOE Low Cost Solar Array Project: Module Automated Assembly Development (Source Ref. 3-4)

Commercial modules are available in a wide range of operating currents and voltages. The most common designs, however, are those with a voltage output, V_{max}, of about 15V (STC); under most operating conditions this voltage output would match the voltage required to recharge a 12V storage battery, viz., about 14.4V. A wide selection of power outputs is also offered, ranging from 1 to 60 W, P_{max} (STC). Module efficiency runs from about 7 to 12 percent (STC). The higher efficiency modules invariably are those using square or rectangular cells that allow higher packing efficiency.

To those concerned with performance measurement procedures and qualification and acceptance test specifications for modules, two publications are of value. "Terrestrial Photovoltaic Measurement Procedures" (Ref. 3-5) deals with both indoor and natural sunlight measurement of modules and a description of test equipment. "Block V Solar Cell Module Design and Test Specifications for Intermediate Load Applications" (Ref. 3-6), treats design and performance requirements; characterization, qualification and acceptance test requirements; performance measurement procedures; and environmental test procedures. Ref. 3-5 is subjoined here as Appendix B.

The manufacturer of silicon solar cell modules is concentrated in the industrial countries--United States, France, West Germany and Japan. Two developing countries have undertaken to produce cells and fabricate modules in modest quantities: India (Central Electronics) and Mexico (Centro de Investigacion y de Estudios Avanzados del Instituto Politicinco Nacional). It is likely that in the near future in-country module manufacturing facilities will be established by several developing countries through joint ventures with Western firms.

(2) Panels and Array. A panel is a collection of modules fastened together (usually factory preassembled and wired) to form a unit for field installation. An array is a mechanically and electrically integrated assembly of panels which, together with support structure and foundations, forms the free-standing field installed unit.

Panel assembly usually is most effectively carried out in-plant. Within a protected environment quality control of the physical integration of the modules and support structure and over the electrical interconections and wire routing can be maintained. Also, standardized assembly techniques can be employed to minimize cost and increase productivity. The organization and operation of a panel assembly plant is quite similar to that of other types of product assembly plants now operating in many developing countries. The labor skills required can be provided through short-term or on-the-job training of local unskilled workers. Array installation is a field operation. With an appropriately designed system, much of the on-site work can be performed by local labor appropriately instructed and supervised (see section 8.2).

Several important design and construction requirements must be considered in the fabrication and placement of panels and arrays. These are discussed below. Persons interested in more detailed information are directed to Refs. 3-7 to 3-10.

(a) Structural load requirements. For panels and arrays located between 30° N and 30° S latitudes (i.e., no snow and ice loads) the major structural stress will be from wind loading (pressure), front or back. The loading will be a function of array tilt angle. Panel and array structural design specifications typically are in the range of 40-50 lb/ft^2 (1.9-2.4 kPa) which would accommodate maximum wind speeds of 80-100 mi/hr (36-45 m/sec).

(b) Tilt adjustment. The array is soutn-facing in the northern hemisphere and north-facing in the southern hemisphere. Generally, fixed arrays are tilted to the horizontal at an angle which is close to the latitude angle. Adjustable tilt arrays allow changes in the angle to be made periodically to achieve a higher annual energy collection. Preferaoly, the mechanism for changing tilt should be simple so that it can be effected rapidly by one or two people, without the use of tools.

For arrays arranged in multiple rows, intra-row shading can occur if sun angle, array tilt angle, and row spacing are not properly taken into account. The minimum row-to-row spacing required for no shading between 0900 and 1500 hours at the winter solstice (December 21 in the northern hemisphere or on June 21 in the southern hemisphere), can be found from Fig. 3.2-12.

(c) Structural Materials. Structural members of galvanized steel, aluminum, or chemically treated wood have been used for array construction. The two former materials are likely to be more durable in developing country rural environments. Commercial, preformed metal channels have been used in many array designs to facilitate assembly and installation operations both in the plant and in the field (see Refs. 3-7 to 3-9).

(d) Panel Size and Weight. It is desirable to limit the weight and size of panels to facilitate transportation to the site and handling at the site. The maximum size from this perspective is about 4 ft x 8 ft (1.2m x 2.4m). A photograph of a panel being unloaded from a truck at Tangaye, Upper Volta, is shown in Fig. 3.2-13.

(e) Electrical Wiring. Modules are electrically connected in a panel to form strings and branch circuits. A wiring harness, usually prefabricated and installed in the plant, is secured to the panel structure. It is important that the harness and connector design allow for ease of inspection and check-out and for rapid replacement of modules in the field. Figure 3.2-14 shows a harness design for use in the Schuchuli Village (Arizona, U.S.) Power System.

(f) Mounting/Foundation. For small power applications, panels and arrays may be pole mounted or roof mounted where roof orientation, pitch and structural strength are satisfactory. Most frequently, however, panels and arrays are mounted on the ground. In such cases, a foundation is required. Concrete is commonly used to form either curb or post footing foundations. Of especial interest to developing countries is a low-cost foundation design, Ref. 3-9, which uses local rock and earth-fill and requires only laborers with picks and shovels for emplacement (Fig. 3.2-15).

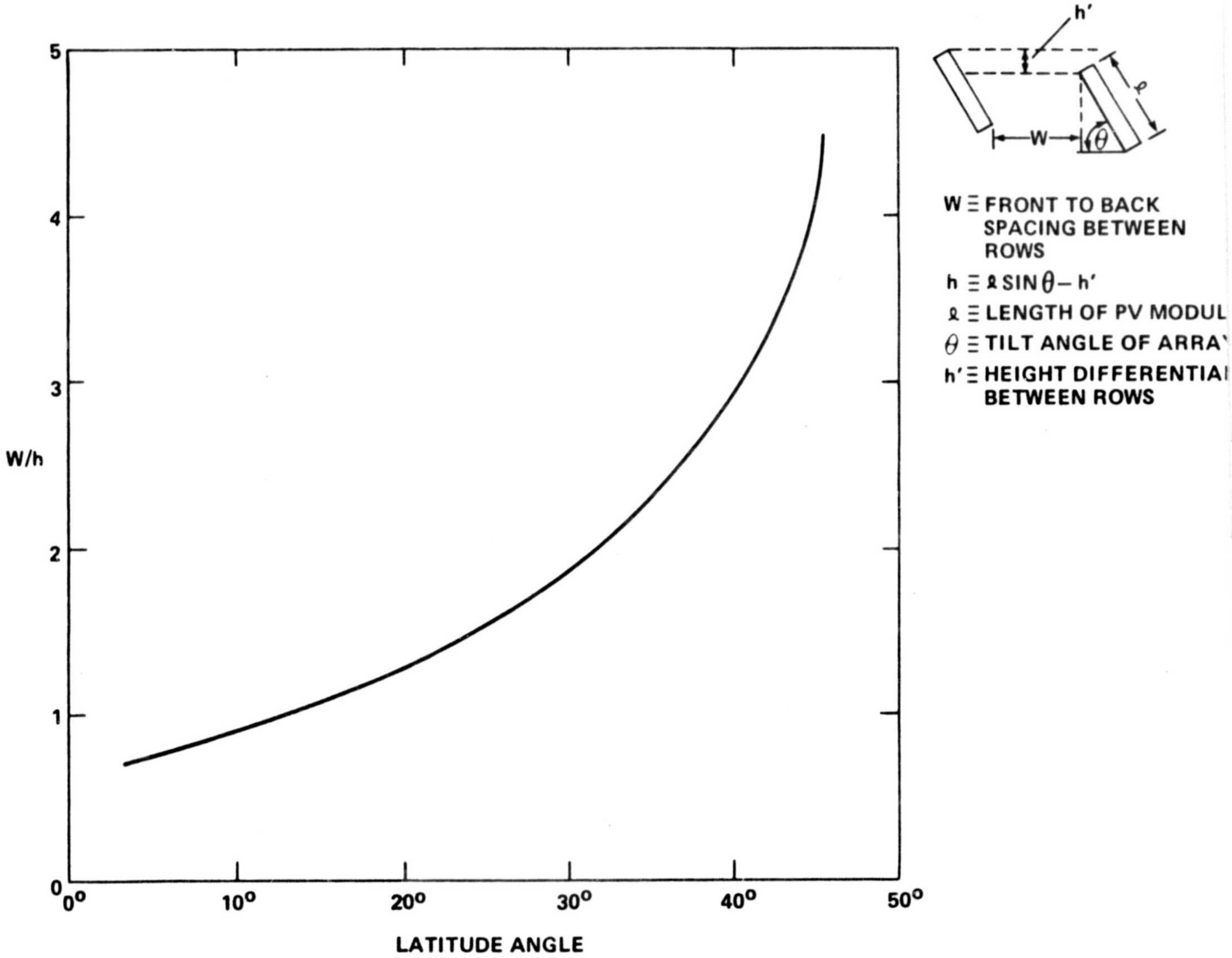

Figure 3.2-12 Minimum Row-to-Row Spacing Required for No Shading Between 0900 and 1500 Hours on Dec. 21 in the Northern Hemisphere and on June 21 in the Southern Hemisphere (Source Ref. 3-11)

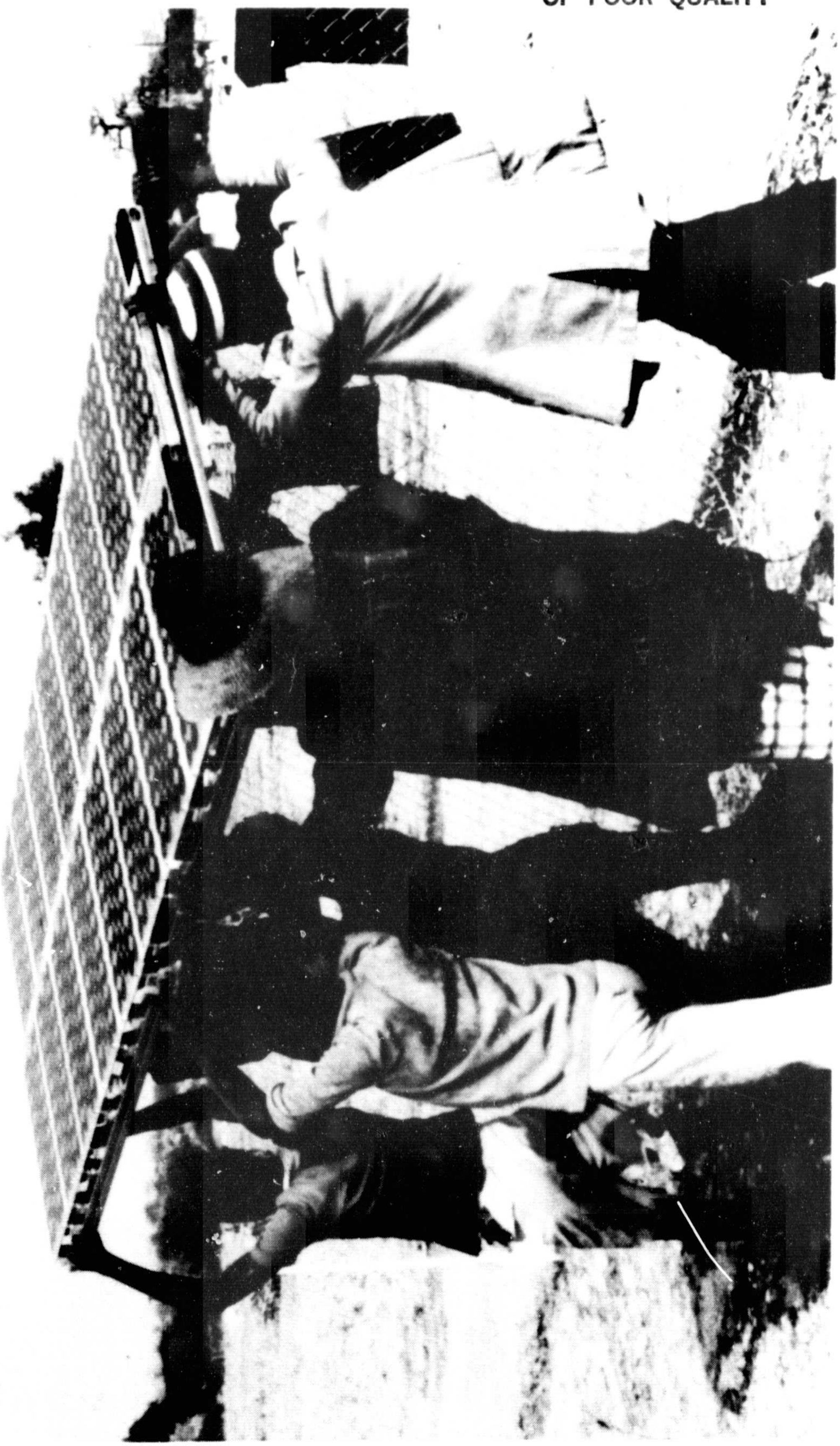

Figure 3.2-13 Handling of Panels for PV Array, Tangaye, Upper Volta

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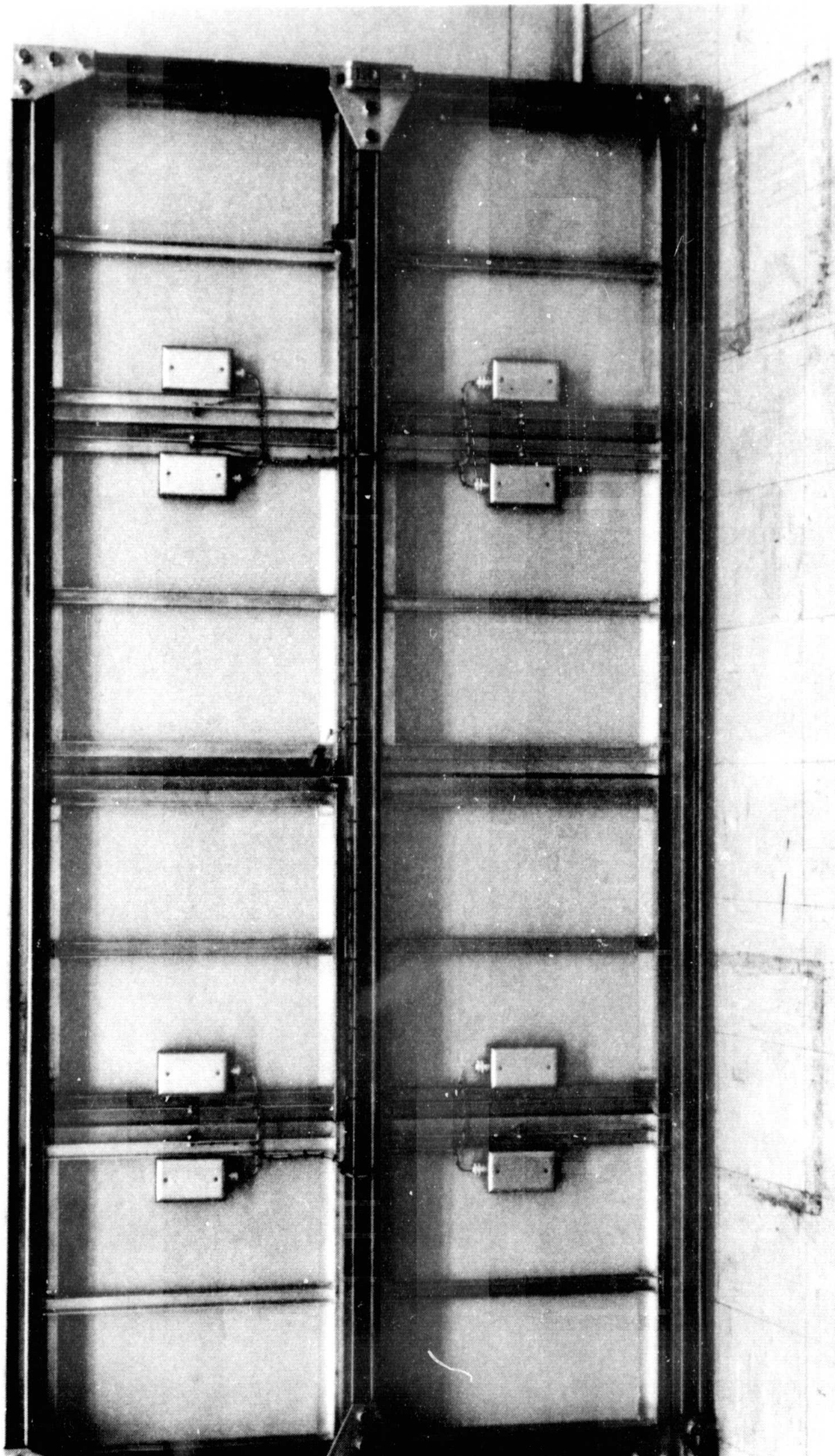

Figure 3.2-14 Rear View of PV Panel and Wiring Harness for Array at Schuchuli, Arizona

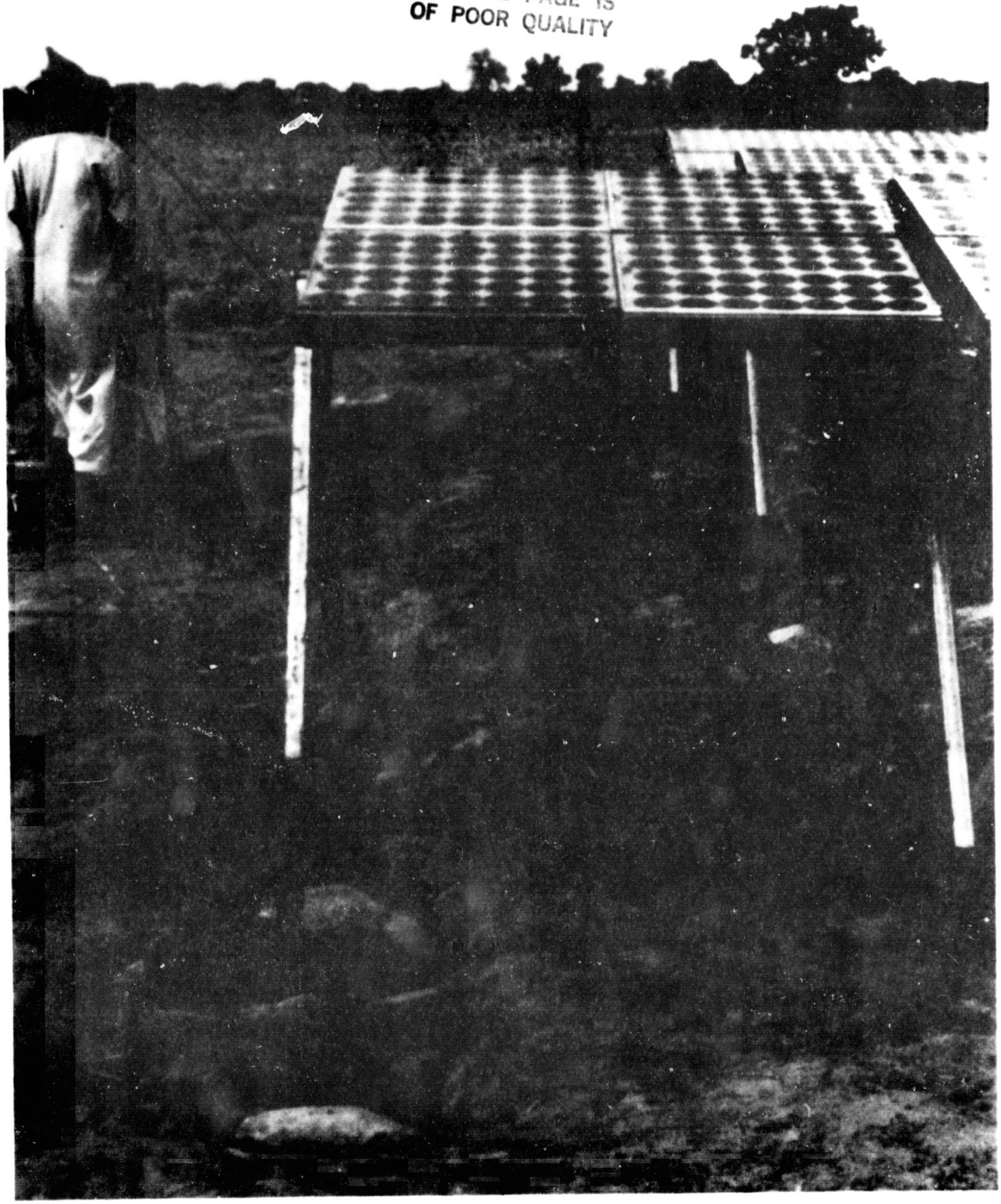

Figure 3.2-15 Preparation of Foundations for PV Array, Tangaye, Upper Volta

3.2.5 Module Reliability

The information discussed below is derived from programs sponsored by the U.S. Department of Energy for PV system tests and application demonstrations managed by MIT-Lincoln Laboratory (since 1976) and the NASA Lewis Research Center (since 1975). The modules tested all employed single crystal silicon cells and were of U.S. manufacture, representing 6 companies and 11 different models and production runs from 1976 through 1979. Modules were purchased through JPL Block Procurements I and II to the respective qualification/acceptance test specifications.

The test data include a total of 11,553 modules used in 22 field tests and demonstrations throughout the United States and also in the Tangaye, in Upper Volta. Test times ranged from 1-1/2 to 5 years duration, with many of the tests still in operation. The index of reliability used is the average monthly failure rate (MFR):

MFR = no. modules failed/total no. modules/no. months in operation

Fig. 3.2-16 provides a summary of this experience. The percentage of the 11,553 modules which fall into one of three reliability groups is as follows: 62 percent acceptable (MFR, 0 - 0.1 percent); 26 percent marginal (MFR, 0.1 - 0.25 percent); 12 percent unacceptable (MFR greater than 0.25 percent).

It should be recognized that PV modules are the products of a fledgling industry and have undergone almost annual design and production changes since 1975. Until design and production methods are stabilized and more field experience is acquired, it is likely that the quality of modules will remain variable. Given this situation, a prudent buyer should obtain some protection by negotiating an appropriate warranty. For very large purchases, or where an application places a premium on reliability, a purchaser may wish to require certification from the manufacturer that the modules meet appropriate qualification and acceptance test specifications. In this regard, the most recent JPL specifications may be of assistance (Ref. 3-6).

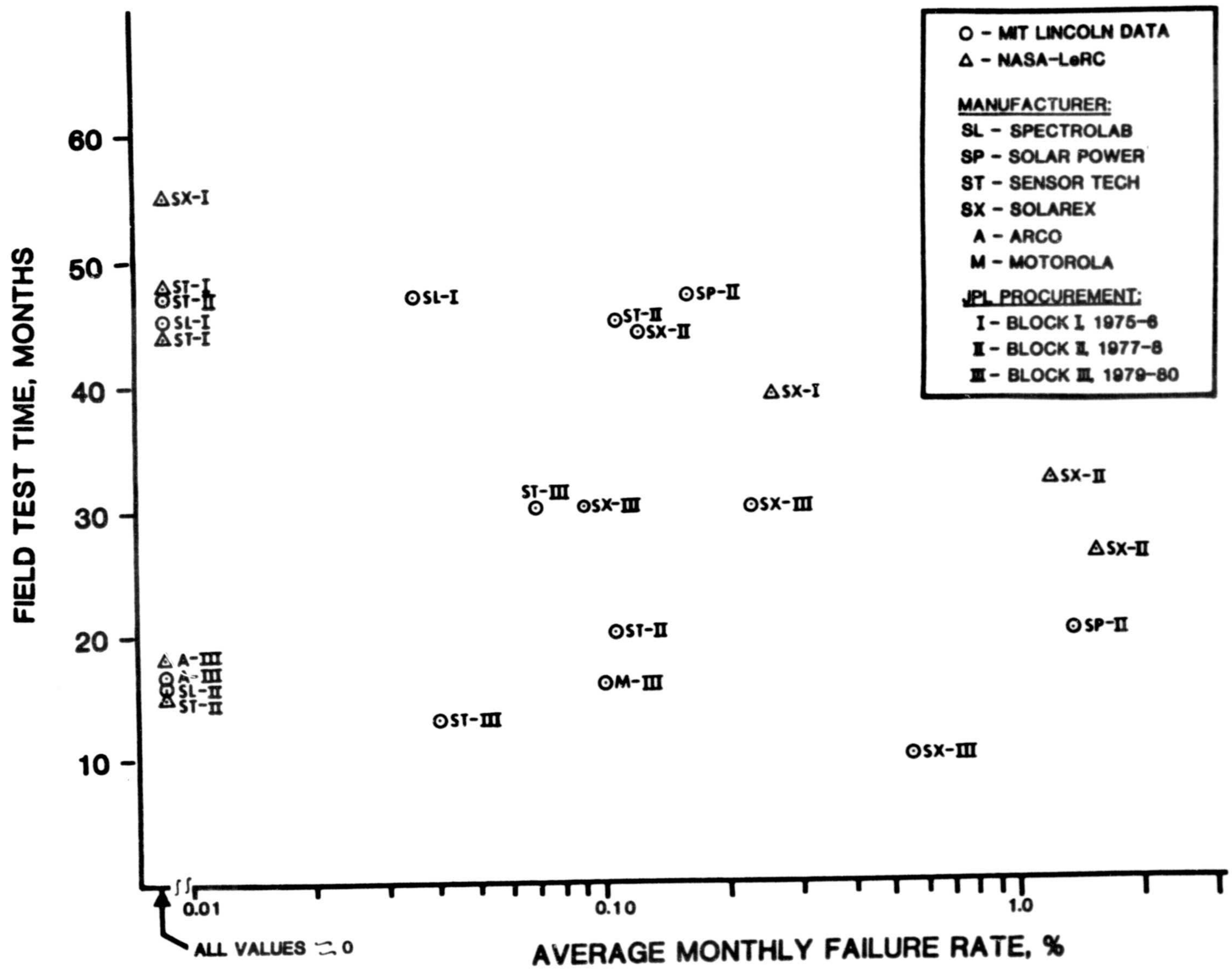

Figure 3.2-16 PHOTOVOLTAIC MODULE RELIABILITY EXPERIENCE

Because of the electrical circuit redundancy that can be designed into arrays, when module failures do occur, they seldom result in a total system outage. This is the preeminent fact concerning module reliability. Even in an extreme case when cumulative module failure reached 30 percent (see section 10.2) the system experienced no down-time; rather, there was a cumulative reduction in total energy delivered by the array. This gradual reduction in energy output over several months necessitated either temporary, partial load shedding or reduction in hours-per-day of operation.

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4.0 STORAGE BATTERIES

4.1 Role of Storage Batteries

Because of great diurnal and seasonal variations in solar insolation, a battery may be used in most PV systems to perform two essential functions: power buffer between the array and loads and 2) energy storage bank.

(1) Power Buffer. The PV array is neither a constant current nor a constant voltage source. The maximum power output of the array (the product of the current and voltage at the maximum power point) will vary with solar insolation and temperature conditions, as with the size of the load that can be powered by the array. Figure 4.1-1 displays representative i-V curves for a 3 kW (STC) array at several specific times during the day. In the early morning or late afternoon, a load that draws, for example, 1425 W (50 percent of P_{max} at noon) could not operate. Also, for similar reasons, the array may not be able to supply power to loads with short high peak demand characteristics such as during motor-startup.

On the other hand, batteries are, in effect, a constant voltage power source (Fig. 4.1-1). In this regard, when used in a PV system, a battery acts as a buffer between the array output and the load, compensating for the limitations of the array and enabling all design load demands (including peak power demands) to be met.

(2) Energy Storage. Solar insolation varies during the year, usually peaking in the summer and bottoming in the winter. Superimposed on this general pattern are the effects of seasonal climatic conditions (e.g., monsoon and harmattan). A representative example of monthly average insolation (in units of kWH/day) on a horizontal surface for Gao, Mali, 16° N latitude, follows.

J	F	M	A	M	J	J	A	S	O	N	D	Ann. Aver.
5.15	5.47	5.92	6.39	6.39	6.04	6.16	6.02	5.87	5.50	5.17	4.66	5.73

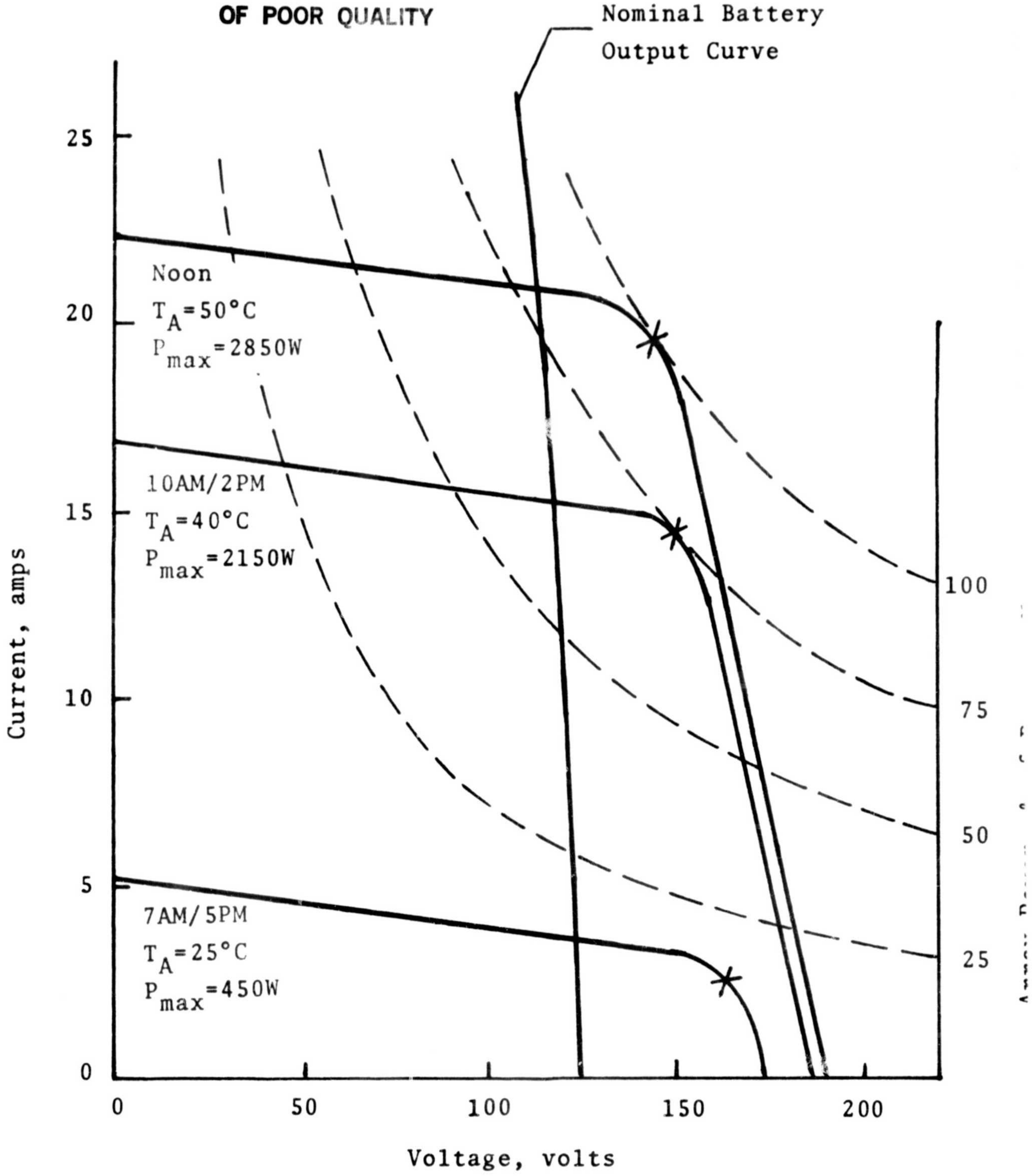

Figure 4.1-1 Representative PV Array and Battery Current-Voltage Curves

With an overall efficiency of 10 percent, a PV system should be able to supply an average daily load of 0.573 kWH for each square meter of array. If, for example, we have a 10 m^2 array and a constant daily load of 5.73 kWH, in months of low insolation there would be a shortage of power generated for the load and in months of higher insolation an excess. Similarly, within any given day the sunrise to sunset variations of insolation and cloud cover result in everchanging power generation; and at night, of course, no power is generated. To allow uninterrupted operation of loads in all seasons and times a storage battery is used to compensate for the total absence of reserve energy capacity in the array. An appropriately sized battery can store excess electrical energy generated during periods of high insolation and release it as needed during periods of low, or no, insolation.

4.2 PV Battery Duty Cycle

The operating regime for a battery used in a PV system is determined mainly by the following factors: (1) the array and battery size, which is a system cost trade-off decision; (2) the battery operating temperature, which is site and enclosure related; (3) the battery discharge rate, which is a function of load profile; and (4) the diurnal and seasonal variations of insolation. Figure 4.2-1 provides an idealized example of a PV battery annual duty cycle as represented by the battery state-of-charge (SOC). Battery state-of-charge is the available energy capacity of the battery expressed as a percentage of the rated capacity at 25° C. From full charge at the end of summer the battery declines to its lowest state-of-charge by the end of winter, then gradually increases in SOC till it is once again at peak charge by the end of summer. Thus in times when the insolation is insufficient to meet the load requirements the energy deficit is compensated by withdrawing energy stored in the battery. When insolation is greater than that needed to meet the load requirement, excess energy is stored in the battery.

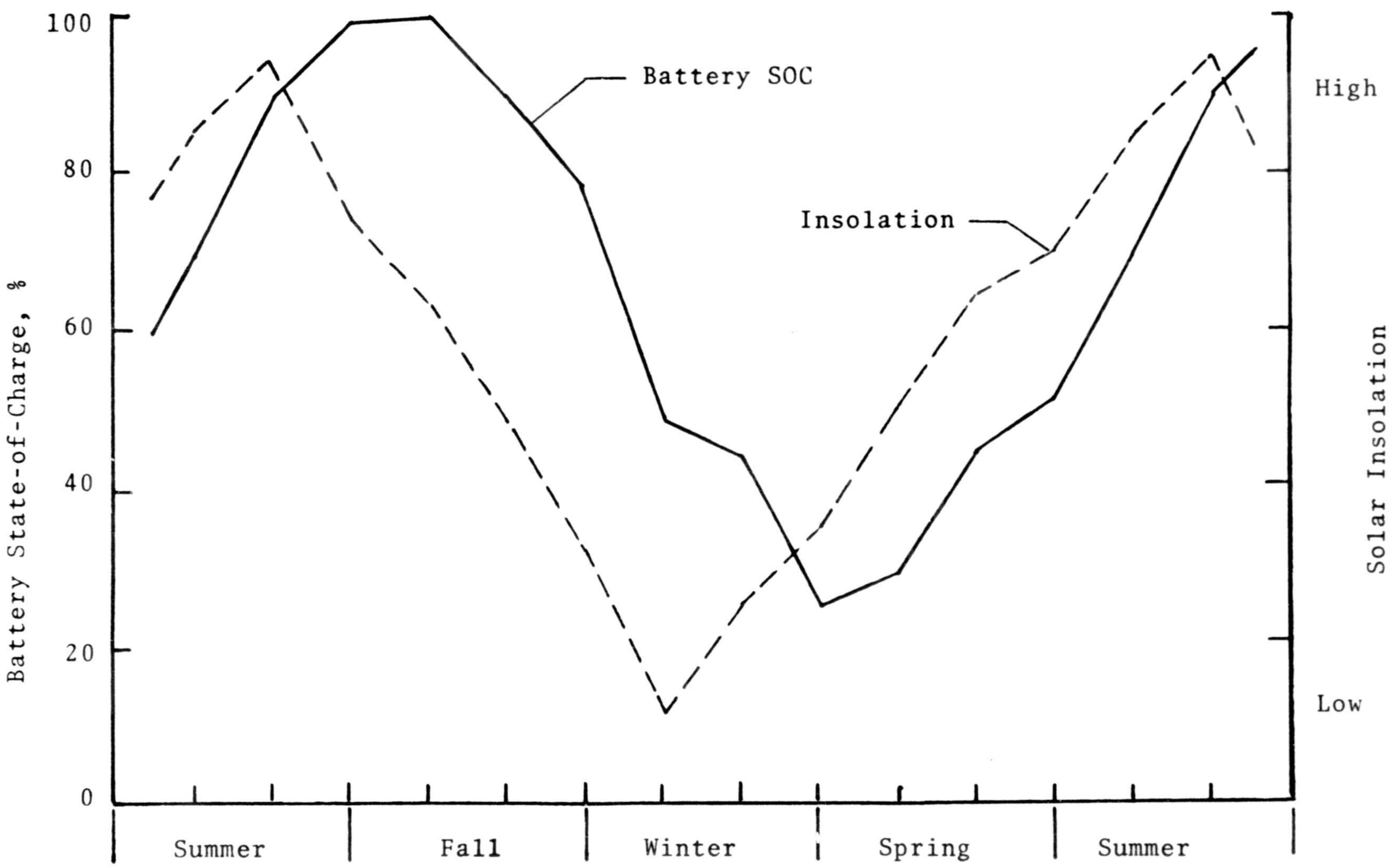

Figure 4.2-1 Example of PV Battery Annual Duty Cycle

Annual changes in battery SOC are the result of the continuous day-by-day incremental variations in SOC. Figure 4.2-2 provides an example of PV battery diurnal duty cycle for two consecutive days on the springtime portion of the curve in Fig. 4.2-1.* During the daylight hours, more energy is generated than is required by the loads and the excess is stored in the battery. During the night, the battery supplies the load requirement. At the end of day 1, there is a net gain of 0.5 percentage points in battery SOC, while by the end of day 2--a cloudy day--there is a loss of 0.2 percentage points in SOC from day 1. Throughout the year, each daily increment or decrement contributes to produce the annual duty cycle.

Duty cycles in the examples given are for a specific array size, battery size (i.e., energy capacity), battery operating temperature, and load profile. A change in any of these factors will produce a different set of annual and diurnal duty cycles. It should also be evident that even for a fixed set of conditions the battery duty cycle will not be identical year to year. Due to the stochastic (random) nature of weather conditions, insolation will deviate daily and annually about certain long term average values; so too will the duty cycle.

4.3 Commercial Battery Types

The two battery types that have been used for PV systems are lead-acid and nickel-cadmium. Due to higher cost, lower energy efficiency and limited upper operating temperature (40°C), nickel-cadmium batteries have been employed in relatively few systems.

The lead-acid battery is a lead/sulfuric acid/lead dioxide electrochemical system, whose overall reaction is given by the following equation:

$$PbO_2 + Pb + 2H_2SO_4 \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} 2\,PbSO_4 + 2H_2O$$

*Note that the references to seasons here and in Fig. 4.2-1 are valid for temperate zones of North America. The reader will recognize corresponding periods in other geographic areas.--Ed.

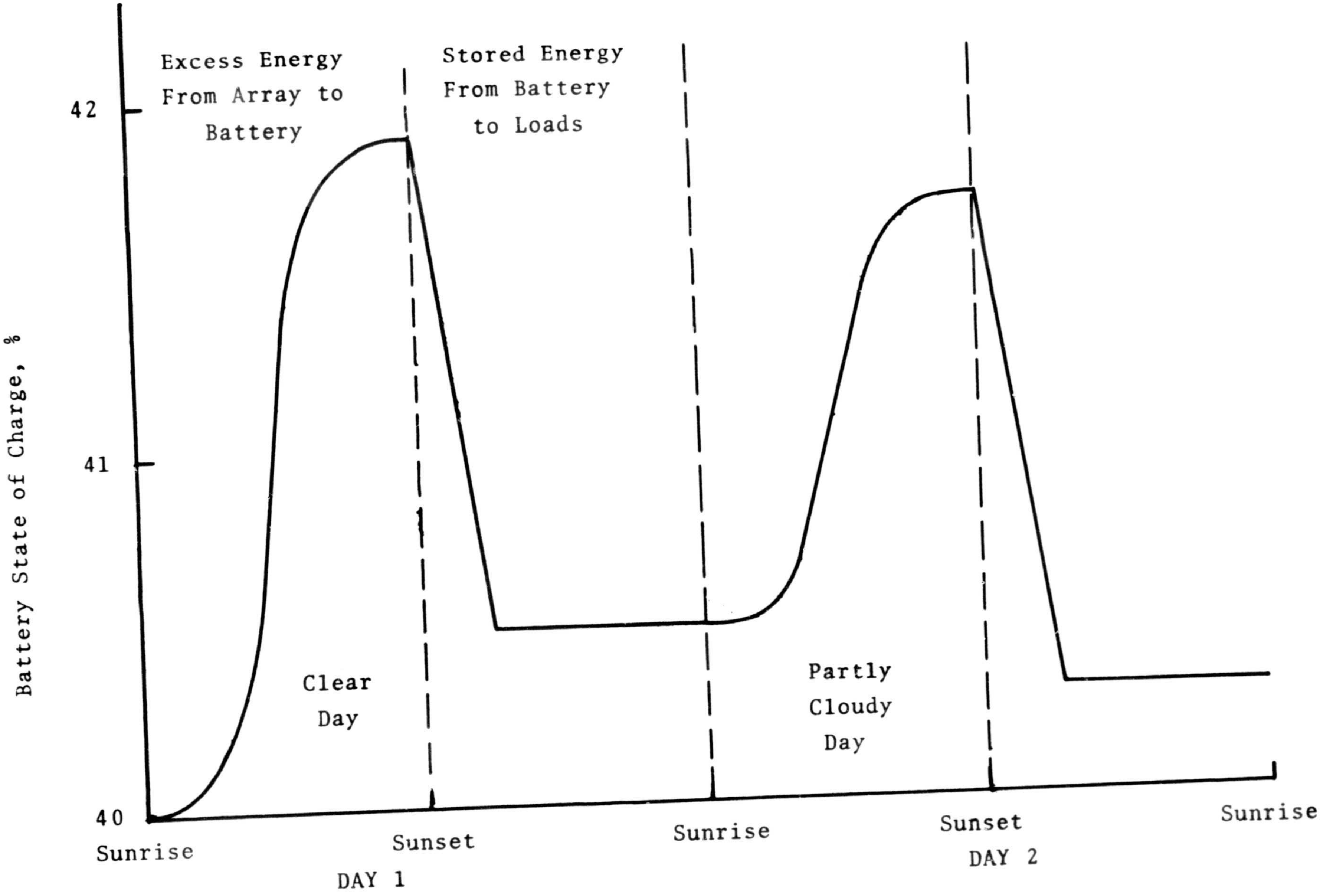

Figure 4.2-2 **Example of PV Battery Diurnal Duty Cycle**

(Two-Day Period During Spring, Figure 4.2-1)

The active material of the positive and negative plates (lead dioxide and sponge lead, respectively, in a fully charged battery) are usually supported on a lead grid structure. In some cells a small amount of antimony or calcium is alloyed with the lead to strengthen the grid and increase life. The plates are immersed in dilute sulfuric acid electrolyte and contained in a rubber or plastic case.

A battery is made up of two or more electrochemical cells (the basic electrochemical positive-negative plate pair) interconnected in an appropriate series/parallel arrangement to provide the required operating voltage and current levels. The familiar 12 volt lead-acid battery, for example, consists of six 2-volt cells connected in series and packaged in a single outer case. Cells and batteries are commonly rated in terms of their ampere-hour (AH) current-capacity or watt-hour (WH) energy-capacity. In general usage, the discharge (or charge) rate is the rate of current flow from (or to) the cell or battery, normalized with respect to the rated capacity, C, of the cell or battery. For example the 10-hour discharge rate of a 500 AH battery is expressed as 500 AH/10 H = 50 A = C/10 rate.

Several types of commercial lead-acid batteries have been perfected to perform under the specialized duty cycle requirements of various applications. These are summarized in Fig. 4.3-1. We shall focus upon low rate PV batteries. For a review of other battery types, the reader is referred to Ref. 4-1.

4.4 Stand-Alone PV System Batteries

In the last several years batteries have been made available commercially that are designed to meet the specific requirements of terrestrial, stand-alone photovoltaic power systems. They are optimized to provide the low rate (e.g., C/500) operation typical of these systems, are available with either pure lead or lead-calcium grids to minimize the

Type	General Characteristics	Typical Applications
Automotive (SLI) and Diesel Starting	High discharge rate, relatively low cost, poor cycle life	Automobile starting, lighting and ignition; tractors, snowmobiles and other small engine starting; large diesel engine starting
Motive Power (Traction)	Moderate discharge rate, good cycle life	Fork lifts; mine vehicles; golf carts, submarines; other electric vehicles
Stationary (Float)	Medium discharge rate, good life (years), some types have low self-discharge rates, poor cycle life	Telephone power supplies; uninterruptible power supplies (UPS); other standby and emergency power supply applications
Sealed	No maintenance, moderate rate, poor cycle life	Lanterns, portable tools, portable electronic equipment, also sealed SLI
Low Rate Photovoltaic	Low maintenance, low self-discharge, special designs for high and low ambient temperatures, poor deep cycle life	Remote, daily shallow discharge, large reserve (stand-alone) photovoltaic power systems
Medium Rate Photovoltaic	Moderate discharge rate, good cycle life, low maintenance	Photovoltaic power systems with onsite backup or utility interface, requiring frequent deep cycle operation

Figure 4.3-1 Lead-Acid Battery Types (Source Ref. 4-1)

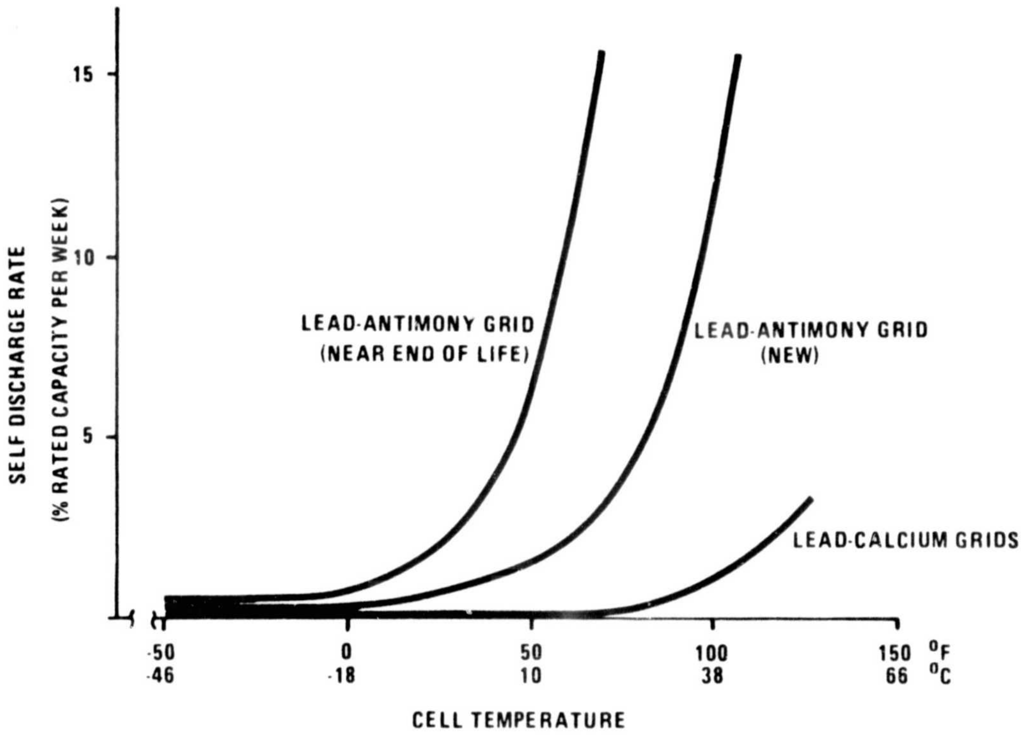

Figure 4.4-1 Lead-Acid Battery Self-Discharge Rate (Source Ref. 4-1)

self-discharge rate, can be purchased in a variety of cell sizes from 50 AH to 3000 AH capacity, and are expected to have useful lives in the range of 5 to 15 years depending on service conditions.

For PV applications a high battery self-discharge rate will adversely affect the overall energy efficiency of the system. All lead-acid cells experience some loss in capacity on standing, due to internal chemical actions. Fig. 4.4-1 presents typical self-discharge rates for cells containing antimony or calcium grids. The self-discharge rate at normal operating temperatures for cells with antimony grids, characteristic of most automotive (SLI) type batteries, is relatively high when new and increases five-fold near the end of life. The self-discharge rate for cells with calcium grids remains relatively low (approximately 0.25 percent per week at 25° C) throughout the life of the cell.

Plots of selected characteristics for a representative PV battery designed for hot climate applications (viz., average annual temperature greater than 32° C), follow and are discussed below. For additional details the reader is referred to the various battery manufacturers' data sheets and test information. A sample data sheet can be found in Appendix C.

(1) Open circuit voltage vs. depth of discharge (DOD) is given in Fig. 4.4-2. Depth of discharge is the obverse of state-of-charge, namely, 100-SOC, in percent. Cell voltage decreases almost linearly with depth of discharge until a point is reached where further discharge results in a more rapid reduction in voltage. Manufacturers usually specify a discharge cutoff voltage just past this point - in this case, 1.95 V and 75 percent DOD. Cells should not be operated beyond the voltage cutoff, because further discharge can result in permanent damage to the cell. <u>The cutoff voltage and DOD limitation is highly significant when sizing a battery for use in a PV system.</u> If, for example, 100 AH of electrical storage capacity is needed to

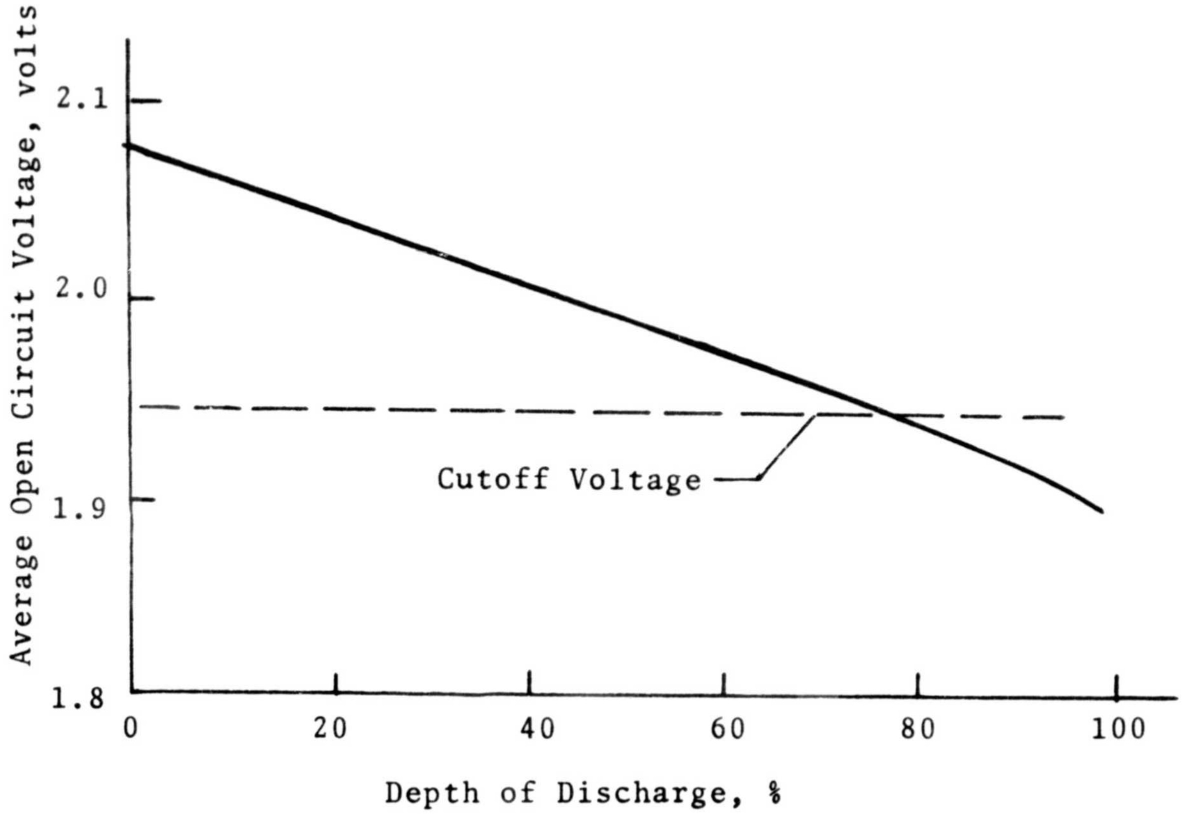

Figure 4.4-2 PV Cell Open Circuit Voltage at Various Depths of Discharge (25°C, C/500 Rate) (Source: Ref. 4-2)

meet system requirements, a battery of at least 133 AH capacity must be purchased:

133 AH, rated capacity x 0.75 DOD limit = 100 AH, available capacity

(2) Available capacity vs. temperature for two rates, C/500 and C/8, is presented in Fig. 4.4-3. The depth of discharge at which the cutoff voltage is reached, at a given discharge rate, decreases with decreasing cell temperature. Therefore, the available capacity of a cell discharged at a given rate to the cutoff voltage also decreases with decreasing temperature, as indicated in Fig. 4.4-3. At temperatures above 77° F (25° C) the percentage of available capacity increases only slightly at the low C/500 rate.

(3) Maximum acceptable cell charge voltage vs. temperature is given in Fig. 4.4-4. Proper charging conditions are essential to achieve acceptable charge efficiencies and maximum cell life. Charging at too high a rate or significantly past 100 percent SOC results in a sharp voltage rise within the cell. This elevated voltage causes excessive production of hydrogen and oxygen (called gassing) which has several detrimental effects. Gassing consumes a portion of the charging current, thus reducing charge efficiency. Gassing creates turbulence within the cell which can dislodge active material from the plates, thereby decreasing cell life. Escaping hydrogen and oxygen can constitute an explosive hazard and also necessitate addition of water to keep the plates immersed and maintain proper electrolyte concentration. The voltage at which gassing begins is a function of temperature so that the maximum acceptable charge voltage, during normal charging, must be adjusted to reflect the actual temperature of the cell. Additional discussion of battery charge requirements will be found in section 5.1.

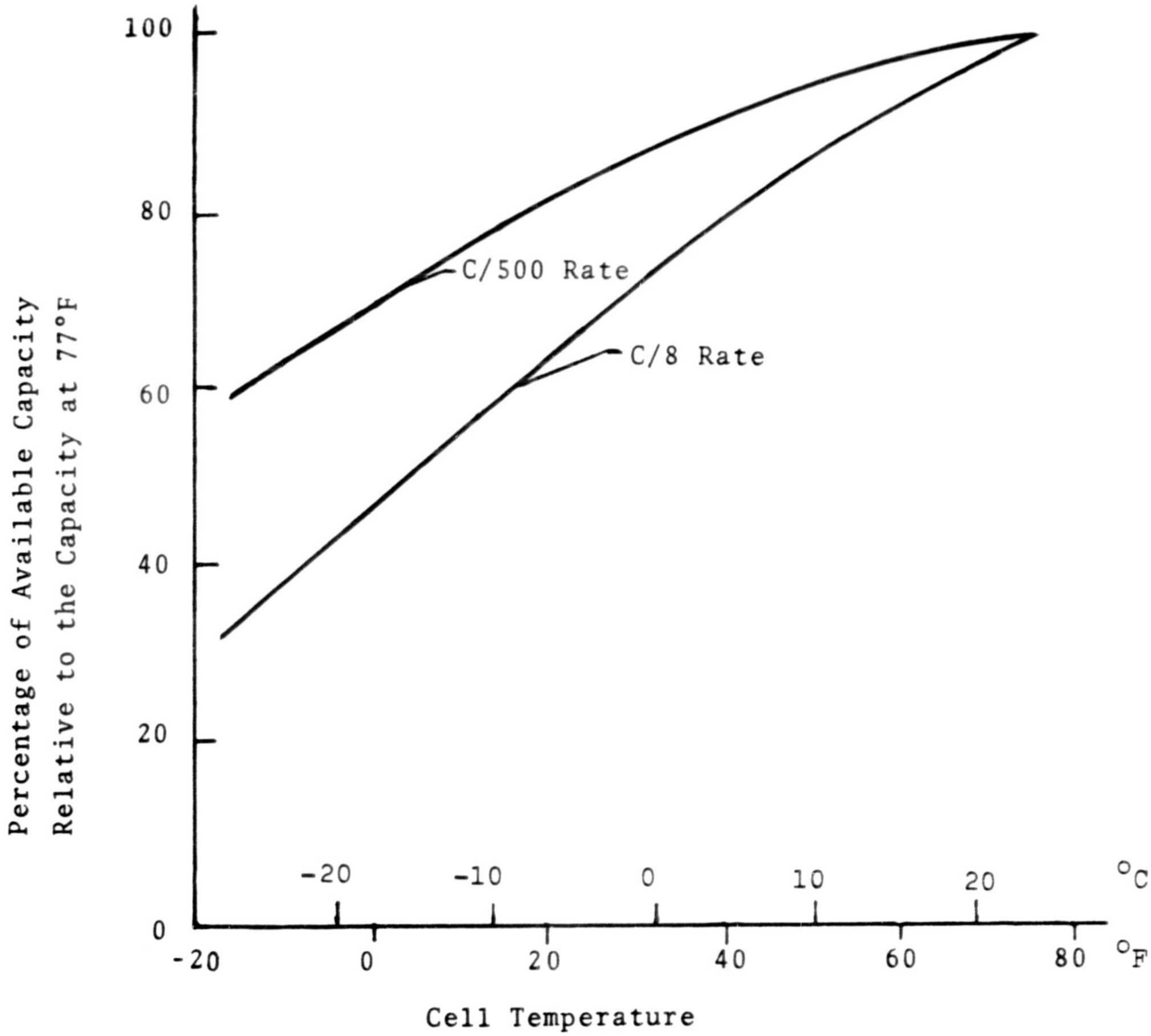

Figure 4.4-3 Cell Capacity vs. Temperature
(Source Ref. 4-2)

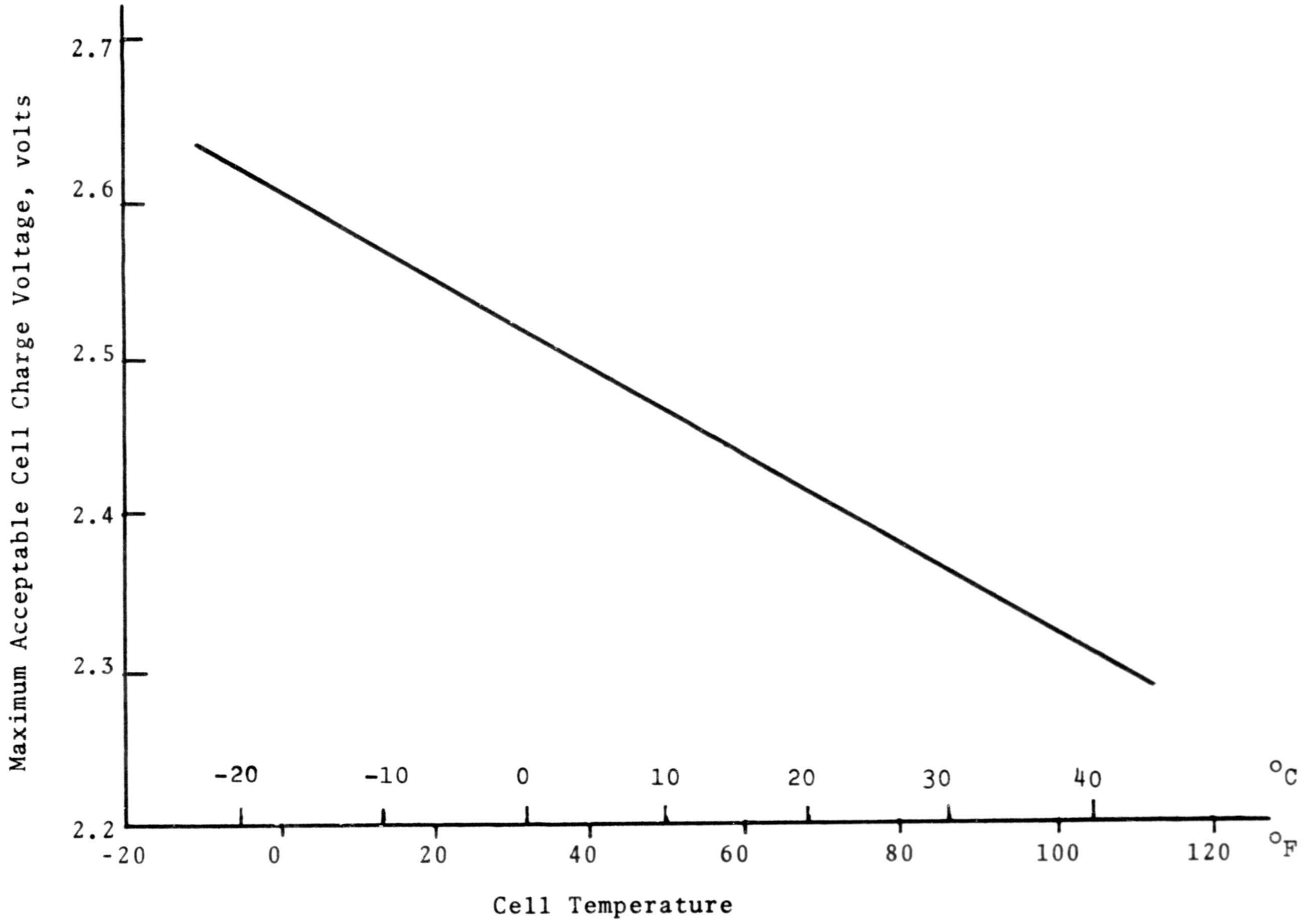

Figure 4.4-4 Maximum Acceptable Cell Charge Voltage vs. Temperature
(Source Ref. 4-2)

SECTION 4
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5.0 REGULATORS AND CONTROLS

5.1 Regulators

For all PV systems except very low power ones with a constant load, a regulator is required to limit array output in order to prevent battery overcharge, overheating and the resulting decrease in battery life. The operational requirements for a PV systems regulator are determined mainly by the nature of the battery-charging process. Ideally, a PV battery charging regulator should be capable of adjusting the amount of charging current to maintain the highest possible rate of charge, consistent with array output and load demand, while avoiding excessive battery gassing.

An example of the level and timing of the charge rate adjustment required for a lead-acid battery can be derived from Fig. 5.1-1, a plot of battery charge voltage as a function of state-of-charge (SOC) for 3 charge rates. Assuming that the battery is 75 percent discharged (i.e., 25 percent SOC) when the charge process begins, it is seen that at the high C/2.5 rate of charge, the gassing voltage is reached when the battery has recovered to only about 60 percent SOC. To prevent excessive gassing, it is necessary at this point to drop to a lower charging rate. If we drop to a C/5 rate, charging would continue at half the initial rate until, at about 80 percent SOC, the gassing voltage is again reached. A drop to a lower rate, say C/20, must then be effected. At the C/20 rate the battery reaches full charge without exceeding the gassing voltage. In this case, the charge voltage curves are for a lead-antimony grid battery. Other battery types would have somewhat different characteristic curves and gassing voltages.

It should be recognized that this example is a simplification of actual cases. In a real situation, the array output current may be less than that required to maintain a desired charge rate, due to changes in solar insolation (caused by changes in sun elevation angle during the day as well as cloud shadowing) and changes in load demand. Nevertheless, the general approach described is applicable to more complex actual cases.

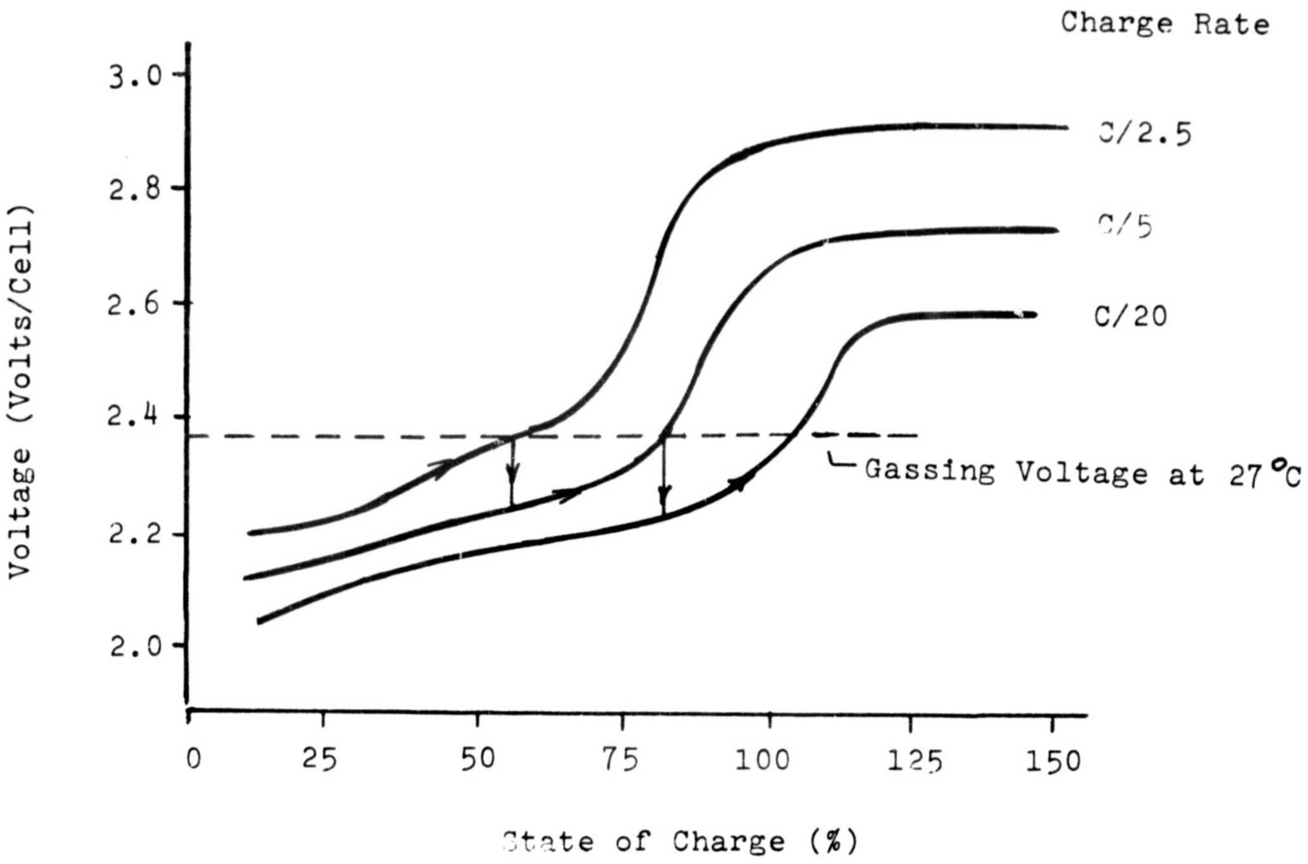


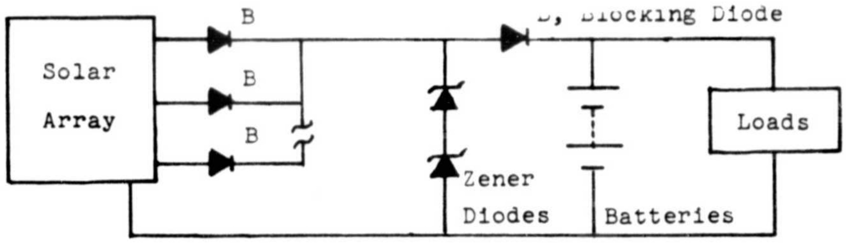
Figure 5.1-1 Lead-Acid Battery (Pb-Sb Grids) Charging Voltage as a Function of State-of-Charge (Source Ref. 4-1)

The example, Fig. 5.1-1, illustrates a 3-step charge rate regulation. Regulation schemes of one step to an infinite number of steps are possible, with a corresponding maximum to minimum battery recharge time, respectively. The one-step (constant current) method constrained to about a C/20 rate, does not allow effective utilization of the PV array output. Two-step regulation, which permits a more rapid recharging, is often used for PV systems. Multiple step regulation schemes are also used, particularly for the large multi-kilowatt systems.

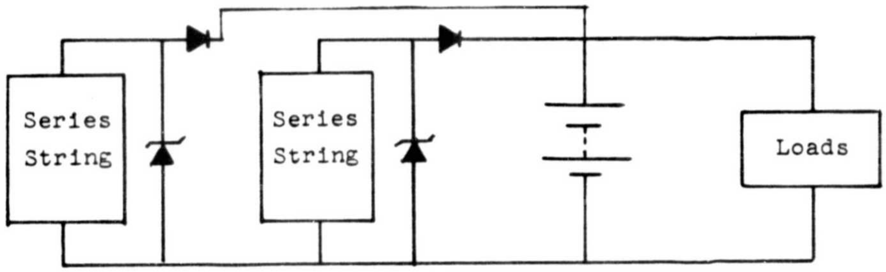
The methods available for PV system battery charge regulation are numerous and varied. For purposes of a general understanding, regulation schemes can be categorized and described by the use of three major characterizing features: (1) method of power dissipation (viz., series or shunt); (2) method of control of the regulator (passive or active); and (3) portion of array output that is regulated (whole array or part).

Shunt-type regulators use Zener diodes, transistors, contactors, or solid-state relays to shunt excess array current to ground (Figs. 5.1-2a-c). Series-type regulators use transistors, contactors, or solid-state relay elements to switch off or reduce the flow of current from the array to the battery (Figs. 5.1-2d-e).

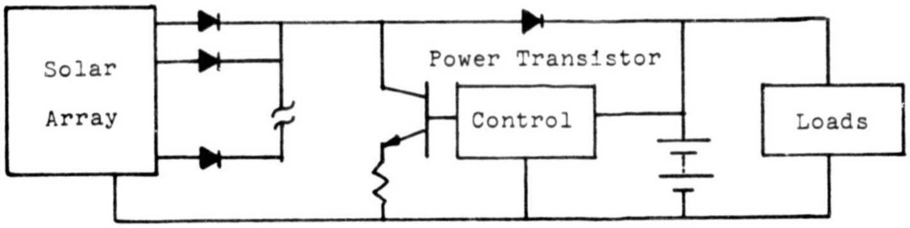
A passive method of controlling the regulation function uses a Zener diode, which allows current to flow when a particular voltage level is exceeded. The Zener diode must be capable of dissipating power equal to the product of the array current and the diode voltage drop. Zener diodes can accommodate power and voltage from a few watts to 50 watts and up to 200 volts. Due to the i-V characteristics of the Zener diode, the passive control method provides "soft" regulation, i.e., a relatively wide voltage cutoff band.



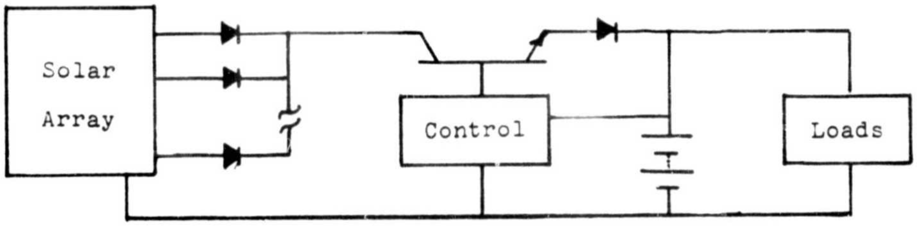
(a) Array,Passive, Shunt Regulation



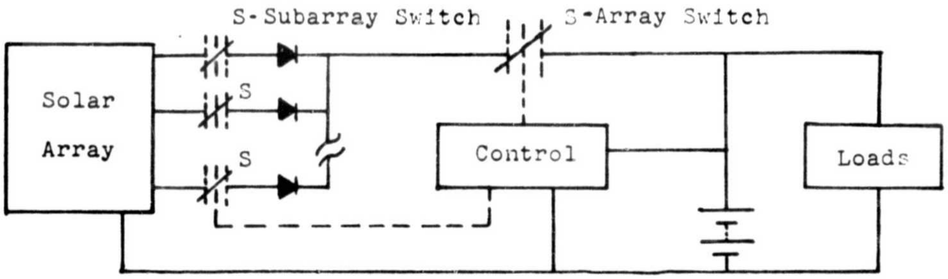
(b) String (or Subarray),Passive,Shunt Regulation



(c) Array, Active, Shunt Regulation



(d) Array, Active, Series Regulation



(e) Array (or Subarray), Active, Series Regulation

Figure 5.1-2 Methods of Power Regulation (Source: Ref. 5-1)

Active controls can provide for more precise voltage regulation, proportional current control, and the adjustment of voltage control level to compensate for battery temperature changes. Power transistors (e.g., bipolar junction diode or Darlington) shunt and series elements with active control are shown in the schematics, Fig. 5.1-2c and 2d respectively. In practice, variations of these general designs are also found where an electromechanical contactor or a solid state relay is substituted for the transistor, as in Fig. 5.1-2e.

Controllers can be designed to activate current-shunting or controlling elements for the entire or for portions of the array output; is effected through taps (connections) to subsections of the array. Controllers may be designed to provide for time modulated on-off control signals. An example of the latter, a duty cycle regulator, incorporates an integrated circuit which can vary the ratio of the on to off time response to system voltage, so as to control the amount of current delivered to the battery. The duty cycle regulator has also been used to regulate array output voltage by series-switching array strings off and on (Refs. 5-2 and 3-9).

Several factors are usually considered in the choice of a PV system regulator. Five of these are discussed below.

(1) <u>Power Loss and Heat Dissipation</u> - The current shunting or power dissipating elements of a regulator all have an intrinsic voltage drop which results in power loss and heat generation when current flows through the element. Typical values of power loss for a 120 volt PV system are as follows:

Device	Percent Power Loss
Series Transistor	up to 10 percent
Shunt Transistor	~ 1 percent
Solid State Relay	~ 1 percent
Contactor	~ 0.1 percent

Satisfactory heat management for all the devices, with the exception of the contactor, requires the use of an appropriately sized heat sink. Because of the 1 to 2 V drop across transistors and solid state relays, their use for series regulation with low voltage output systems may not be desirable.

(2) Tolerance of Environmental Stress - High ambient temperature, dust, and moisture may affect performance or result in failure of the regulator. In high-temperature environments, the use of transistor or diodes as linear elements in control systems is to be avoided. Devices which are vulnerable to dust and moisture, such as contactors, must be housed in a weather-tight box if they are to provide satisfactory service.

(3) Reliability - As a general approach, to enhance reliability, regulator parts are derated to provide increased environmental stress margins and sealed and packaged in weather-proof housing.

(4) Cost - Regulator cost is usually a very small fraction (~ 2 percent) of the total PV system cost. On the other hand, the battery, which the regulator protects, can constitute 15 percent or more of the system cost. Savings in purchasing the regulator, at the expense of performance, may prove to be false economy.

5.2 Controls

5.2.1 Battery and Load Protection

In addition to voltage control, some PV systems utilize a high and low voltage limit control to safeguard the battery and the loads. Too high or too low an operating voltage is greatly detrimental to battery life. Customarily, the high voltage limit is set just above the battery gassing voltage, while the low voltage limit is set at the manufacturer's recommended battery discharge cut-off voltage. Extremes of voltage are also harmful to certain loads,

such as drive motors and electronic equipment. Figure 5.2-1 shows a diagram of a PV system with high-low voltage limit control. For safety and reliability, the control subsystem should be independent of other regulation and control subsystems.

5.2.2 Maximum Power Tracking

For certain applications (e.g., systems connected to electrical grids and water pumping), it may be considered desirable to eliminate the battery. Yet, as discussed in section 4, PV systems without battery storage cannot be used effectively to supply power to a fixed load at off-design conditions (e.g., low insolation) since the load demand current will force the array to operate at a power point much lower than the maximum power point (see Fig. 4.1-1). To overcome this difficulty, maximum-power-point-tracker (MPPT) control systems have been devised. These controllers use a feedback method to determine the operating point and a pulse width-modulated (dc-dc) downconverter to provide a constant voltage to the load.

A MPPT unit tested at MIT/Lincoln Lab (Ref. 5-3), exhibited an overall power efficiency of 93 to 96.5 percent, depending on the input and output operating points. The unit was used to couple a 240 watt array to a pump set driven by a 1/3 HP dc motor. Overall, the PV system with the MPPT was estimated to pump 7 percent more water than a system without an MPPT, but less water than a PV system with battery storage.

The utilization of an MPPT is a system design trade-off decision, dependent on considerations of cost, efficiency, reliability, maintenance requirements and so forth.

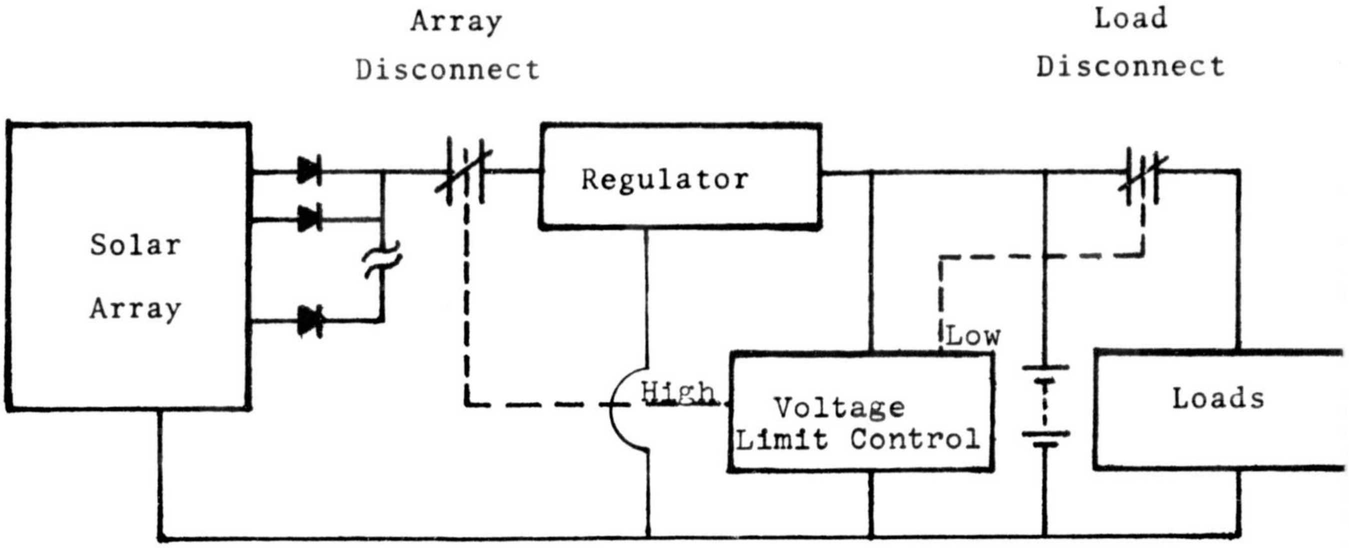


Figure 5.2-1 PV System High-Low Voltage Limit Control

SECTION 5
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6.0 INSTRUMENTATION

6.1 Purposes

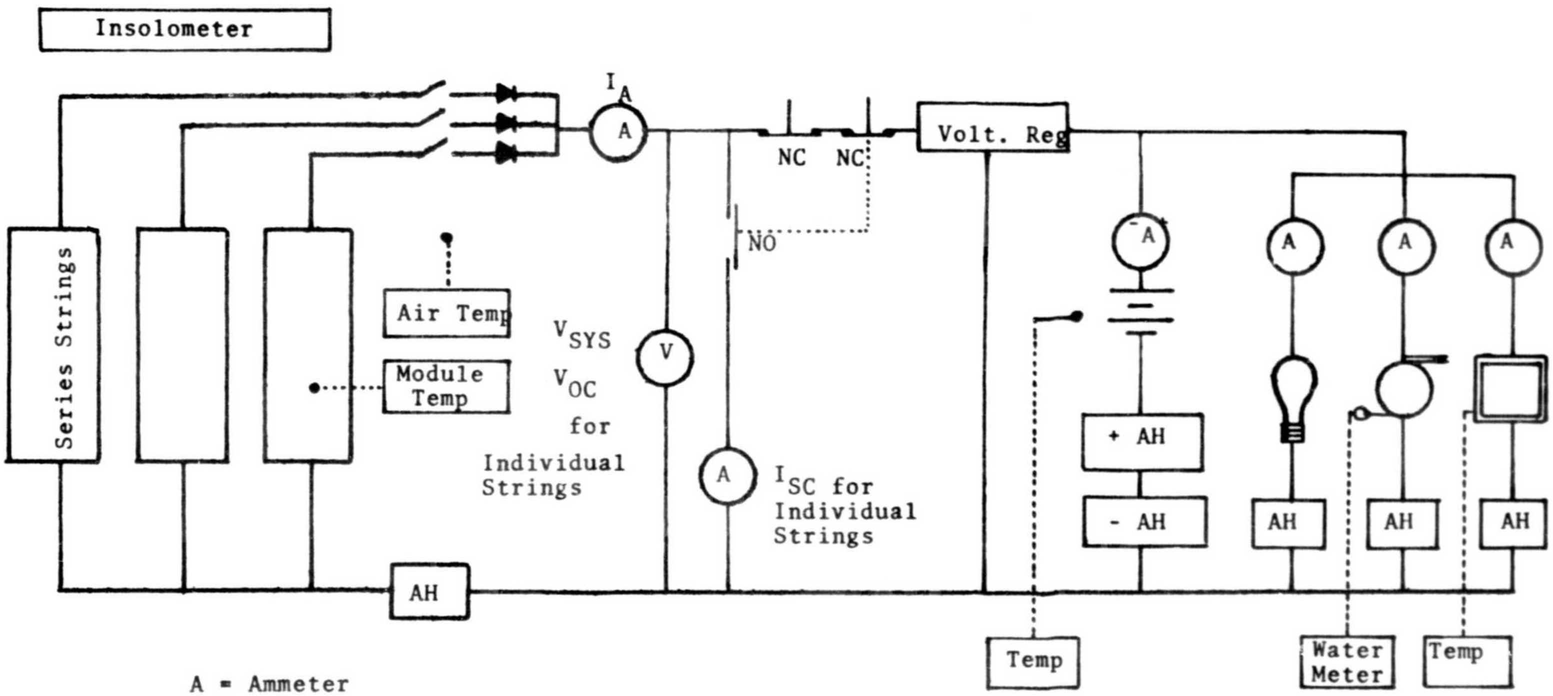
Instrumentation serves two prinicipal functions: (1) to monitor the immediate operation of the system and (2) to measure the cumulative performance of the system. Function (1) instrumentation provides for the diagnostic measurements needed for trouble-shooting and fault correction. Also, it enables an operator to confirm periodically that the system is functioning satisfactorily and to obtain an early indication of conditions that might lead to serious problems. Function (2) instrumentation provides the data needed to verify system and load design and to evaluate long-term system and load performance.

6.2 Types

The type, number and sophistication of the instruments employed depends on the function to be served and the level of precision and accuracy and frequency of data acquisition required by the data analysis. Figure 6.2-1 shows a sample instrumentation schematic for a PV system with three loads: light, water pump and refrigerator.

Panel meters are the least expensive and most trouble-free type of instrumentation. Figure 6.2-2 shows the main instrument panel for the Tangaye Village system which powers a water pump and a grain mill. Periodic reading of the meters and recording of the data by a responsible individual is required. A typical data sheet for the Tangaye system is shown in Fig. 6.2-3. The data sheet was filled out by a village resident who has been instructed in meter reading and data recording procedures.

Automatic recording data systems are relatively expensive, since costs include software and hardware for data processing and analysis as well as the data recording equipment. Automatic systems can provide short interval data,



A = Ammeter
V = Voltmeter
AH = Amp-hour Meter

Figure 6.2-1 Sample Photovoltaic System Instrumentation

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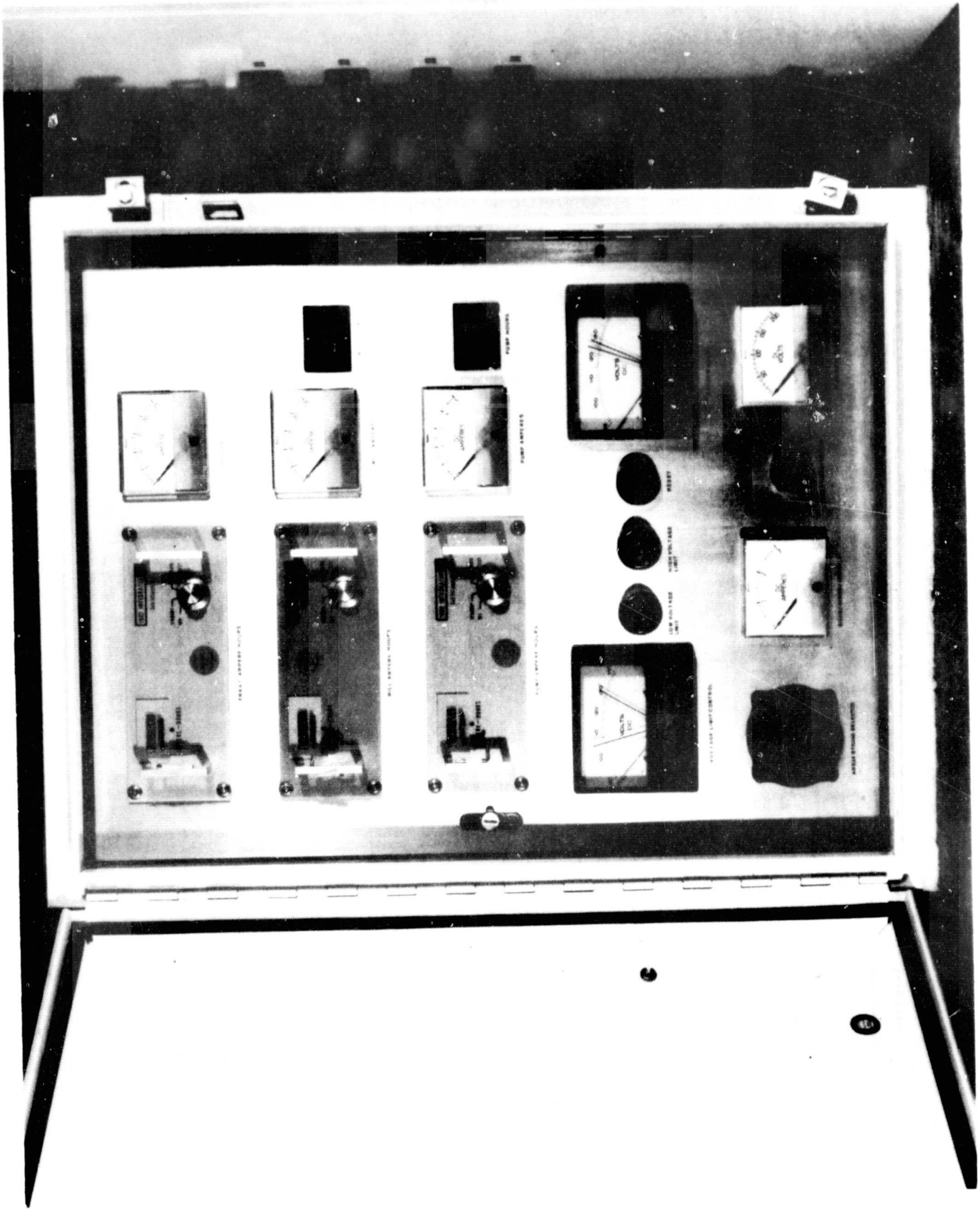

RECORD JOURNALIER TANGAYE

LeRC 04/30/79

Journee de la semaine		Lundi	Mardi	Mercredi	Jeudi	Vendredi	Samedi	Dimanche
Nom		Fernand	Fernand	Fernand	Fernand	Fernand	Fernand	Fernand
Date		8/6/81	9/6/81	10/6/81	11/6/81	12/6/81	13/6/81	14/6/81
Heure		12h5	12h24	12h38	12h10	12h0	12h30	11h24
(1) Array Ampere-Hours		6514.17	6602.84	6679.35	6766.83	6855.37	6936.72	7007.17
(2) Array Amperes		9.5	3.5	3	12.5	6.5	3.5	3
(3) Mill Ampere-Hours		3527.16	3592.37	3645.08	3725.80	3792.47	3850.32	3901.04
(4) Mill Amperes		0	0	0	0	0	0	0
(5) Mill Hours		1785.6	1790.1	1793.8	1799.4	1803.8	1807.8	1811.3
(6) Pump Ampere-Hours		2174.75	2184.04	2182.12	2193.83	2208.33	2214.97	2222.09
(7) Pump Amperes		0.3.1.9	0	0	0	0	0.3.1.9	0
(8) Pump Hours		0072	0081.2	0088.9	0096.3	0104.3	0110.6	0117.3
Voltage Limit Control	(9) Low Limit	104	104	104	104	104	104	104
	(10) Volts	131	134	134	127	126	131	133
	(11) High Limit	137	137	137	137	137	137	137
System Volts	(12) Low Limit	124	124	124	124	124	124	124
	(13) Volts	130	138	133	126	125	130	132
	(14) High Limit	134	134	134	134	134	134	134
Temperature		103	106	103	103	88	95	97
Compteur d'Eau		06722.9	06732.7	06741.3	06749.1	06757.7	06764.4	06771.6
Reservoir d'Eau		1	1	1	1	1	1	1
Temps		0/10	0/10	6/10	6/10	10/10	0/10	0/10
Heures de fermeture		4h45	4h15	5h50	5h55	6h5	5h30	6h40
Temps restant sur le Moulin		12h35	12h35	12h50	12h45	2h25	1h15	11h25
Module thermistor		5.10	5.10	5.10	5.10	5.09	5.10	5.10
Ambient thermistor		0.14	0.14	0.14	0.14	0.14	0.14	0.14
Bande								
(15) 12 Volt Voltage		14.5	14.5	14.5	14	13.5	14.5	14.5
(16) 12 Volt Current		+2.5	+3	+2.5	+3.5	+2	+3	+3
12 volt amp hour meter		4339.49	4373.55	4408.60	4435.24	4458.87	4494.40	4526.79
Number of DC lights on		4	5	6	3	2	5	5
Total Poids		112.65	133.9	131.95	181.3	154.75	109.25	221.18

Figure 6.2-3 Typical Data Record Sheet, Tangaye Village PV System

recorded on tape cassette or paper charts. Tape or chart must be replaced periodically, depending on the amount and rate of data acquisition. For most PV stand-alone applications, the use of automatic recording systems is probably not warranted.

SECTION 6

REFERENCES

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7.0 SAFETY

System design and operating procedures must be adequate to prevent injury to people and to prevent or minimize damage to the equipment. Protective measures to insure safety are discussed below in relation to several major potential hazards.

7.1 Electrical Shock

Any PV system with voltages above 50V d.c. offers a potential lethal shock hazard to people or livestock. Protective measures are as follows:

(1) Floating lines - a wiring arrangement in which both the positive and negative (neutral) power mains float (i.e., have a high resistance path) with respect to earth ground. This will preclude the likelihood of ground fault currents above the physiological let-go level of about 6mA d.c.

(2) Structure grounding - accomplished by use of a buried metallic counterpoise, connected to the array structure and to the power control panel frame. Connections to the array structure should be made at several locations to insure equipotential bonding.

(3) Disconnects - used to isolate parts of the system prior to maintenance operations or to short ("crowbar") the power mains to collapse the voltage in an emergency situation. Switchgear and circuit breakers rated appropriately for current and voltage should be employed.

(4) Line fault detector/relay - a sensor circuit that detects the flow of a current from line to ground and activates a warning signal and/or a rapid crowbar or disconnect.

(5) Fuses or circuit breakers - appropriately located to protect equipment from overload.

(6) Opaque covering for panels - an added safety measure when servicing panels (> 50 V_{oc}) during the daytime. A piece of thin, black plastic is satisfactory. Panels (> 50 V_{oc}) should be washed at night.

(7) Security fence - to keep out unauthorized persons who might harm themselves or the system. In many rural situations the fence is needed to protect the system from domestic livestock.

7.2 Battery

Potential battery-related hazards are from electrical shock, acid spillage, and hydrogen explosion. A more detailed discussion of battery hazards and preventive measures can be found in Ref. 4-1 and Appendix F.

(1) Electrical shock - general preventive measures are discussed in section 7.1. Exposed cell connectors pose a specific hazard. These should be capped or covered. Metal tools used around the battery should have insulated protective handles.

(2) Acid spillage - direct contact with the battery electrolyte, a mixture of sulfuric acid and water, can severely burn the skin and permanently damage the eyes. A supply of fresh water is required in the battery area to flush skin and eyes of person splashed with electrolyte.

(3) Hydrogen explosion - hydrogen liberated during the charging cycle can accumulate in an unvented room or enclosure and may result in an explosive mixture, viz., above 8 percent concentration of hydrogen in air. A flame or a spark could then cause an explosion. This can be avoided by providing adequate ventilation, ensuring that no flame- or spark-producing devices are installed in the battery area, and prohibiting personnel from smoking in the area. Use of flame arrestors on the cell prevents destruction of the cell by ignition of generated hydrogen.

7.3 Load Equipment

Load equipment that turns on automatically (such as a pump that starts when the water in a storage tank drops to a predetermined level) should be enclosed so as to prevent injury to bystanders. Such equipment should also have a local on/off switch to deactivate the unit during maintenance.

7.4 Lightning

The danger to a system from lightning is site-specific. In regions of known high thunderstorm activity (> 25 storm days per year) it may be advisable to install grounded lightning rods to divert induced currents to earth. In all cases system grounding, as described in section 7.1, provides a non-destructive path to ground for lightning surges.

SECTION 7
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8.0 INSTALLATION, OPERATION AND MAINTENANCE

8.1 Site Survey

Prior to the installation of a PV system, in order to obtain information to determine system and load requirements and to select a specific location for the installation, it is advisable to make site surveys. This is particularly valuable in projects of national or regional scale where variations in climatic, geographic, and sociologic conditions are likely to exist. A sample site inspection checklist can be found in Appendix D.

8.2 Installation and Checkout

It is advisable for all field installations, that as much system assembly as possible be carried out in factory or workshop. Array panels, regulators, controls, instrument board and so forth can be assembled, and checked out before shipping to an installation site.

Installation requirements at a site fall into two general categories: construction and electrical. These are summarized briefly in Fig. 8.2-1.

Labor skill requirements depend on the amount of prior assembly. The construction tasks generally can be performed by local unskilled labor under the direction of an experienced individual. Figure 8.2-2 shows the installation of the array supports for the Tangaye Village PV System by local people. The electrical tasks require skilled electricians; nevertheless, where repetitive hookups are involved, local people can be trained to do the job under the supervision of an electrician. Figure 8.2-3 shows electrical connections being made at module junction boxes by villagers at Tangaye. The system checkout task following installation must be undertaken by trained individuals who are acquainted with the design and function of the system.

Fig. 8.2-1 Installation Requirements Summary

Construction

Task	Comments
Site Preparation	Removal of brush, leveling, and drainage
Fence Installation	Around perimeter of array
Pole Line Installation	As required
Array Emplacement	Foundation construction and erection of array support structure.
Buildings/Enclosures	To house instrumentation, controls, switchgear and battery, as required.
Underground Conduit or Overhead Lines	Power and control lines between array and power and control panel.
Load Installation and Enclosure	As required.

Electrical

Task	Comments
Array Wiring	Connection of panels, branch circuits and power buses.
Power Distribution Subsystem	Connection of regulator, controls, instrumentation, safety and electrical protection circuits, and battery.
Load Wiring	As required.

Figure 8.2-2 Installation of PV Array, Tangaye Village

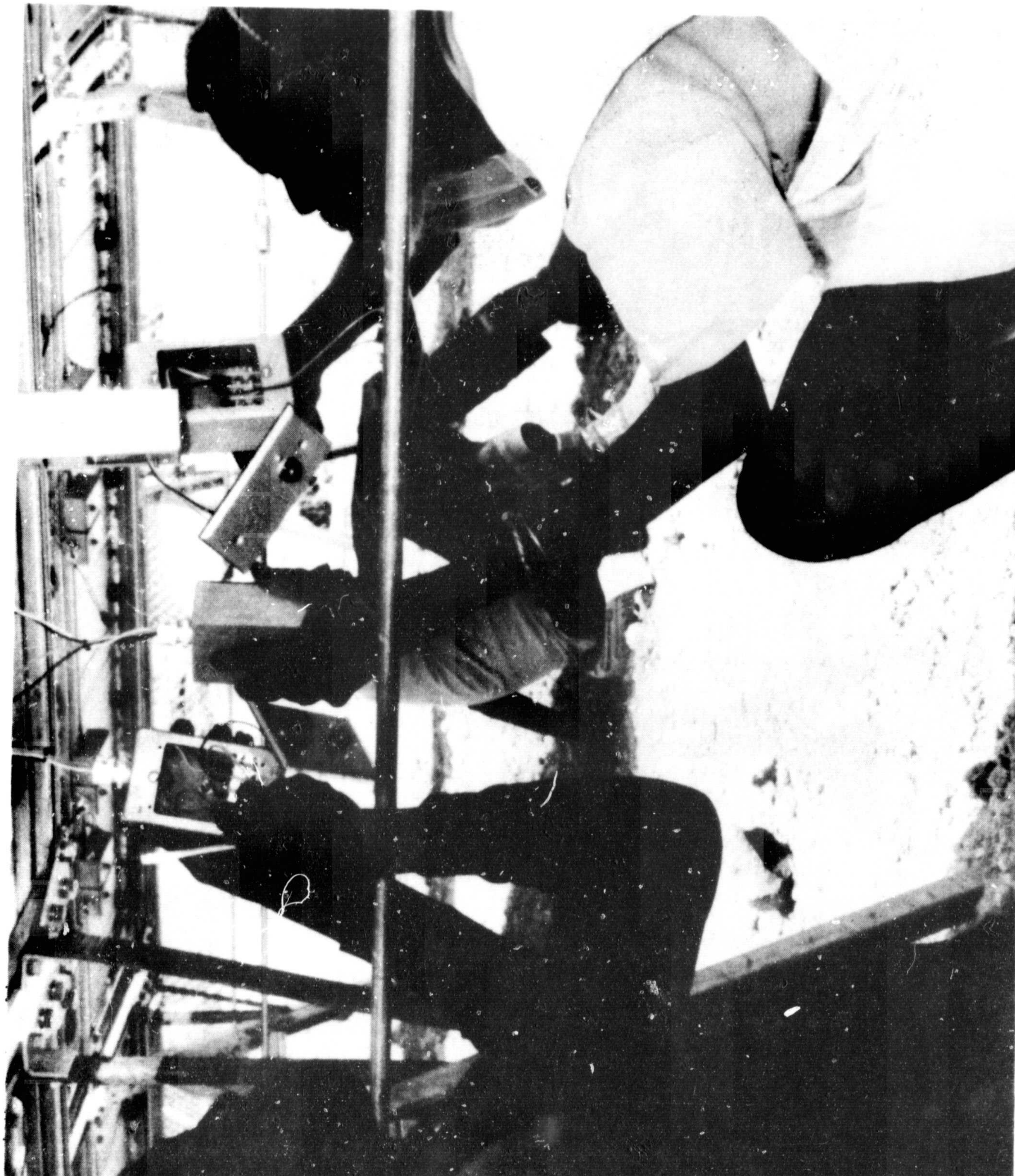

Figure 8.2-3 Electrical Wiring Work for PV Array, Tangaye, Upper Volta

Small, packaged, complete systems sold by various manufacturers usually come with detailed installation and checkout instructions. An example of such instructions can be found in Appendix E.

Battery installation for relatively large systems requires special attention. Individual cell weight can range from 50 to 150 kg (see Appendix C), while whole battery weight could be 1000 kg or more. It is necessary to provide stable support for the battery by means of an appropriately designed foundation, floor, and racks. Appendix F provides detailed information on battery installation requirements and procedures.

8.3 Operation and Maintenance (O and M)

A person is not required to attend to a stand-alone system, under normal conditions. A person is needed, however, to perform inspection and preventive maintenance every 4 to 6 weeks, depending on system complexity and location. Typical tasks are listed below.

(1) Check wiring and connectors for cracking, rodent damage, fraying, etc.; check modules for cracked cells, interconnect corrosion, etc.; wash surface as needed.

(2) Check electrolyte level and specific gravity; check battery terminals for corrosion; add water as needed; clean battery terminals and tighten connections as needed; (see Appendix F for further details).

(3) Check instrument calibration; exercise control systems to verify functioning; read all meters and record as per schedule (see section 6.2, for example).

(4) Inspect and maintain system as per manufacturer's recommendations.

(5) Record and report all faults and deteriation detected in system components and functions.

Usually a local person can be trained to perform these several tasks. Figures 8.3-1 and 8.3-2 provide examples of the O and M provided by the Tangaye Village PV System Manager, a young Voltaic with no previous technical training. In Fig. 8.3-1 he is inspecting and cleaning the battery terminals and in Fig. 8.3-2 he is performing a routine check of instruments and controls.

If a partial or total loss in power is experienced, or if anomalies are detected during routine inspection, trouble-shooting will be needed to identify the problem and repairs will have to be made. To successfully accomplish these activities, the services of persons with electrical and electronic skills are required. Replacement parts, as needed, must also be available.

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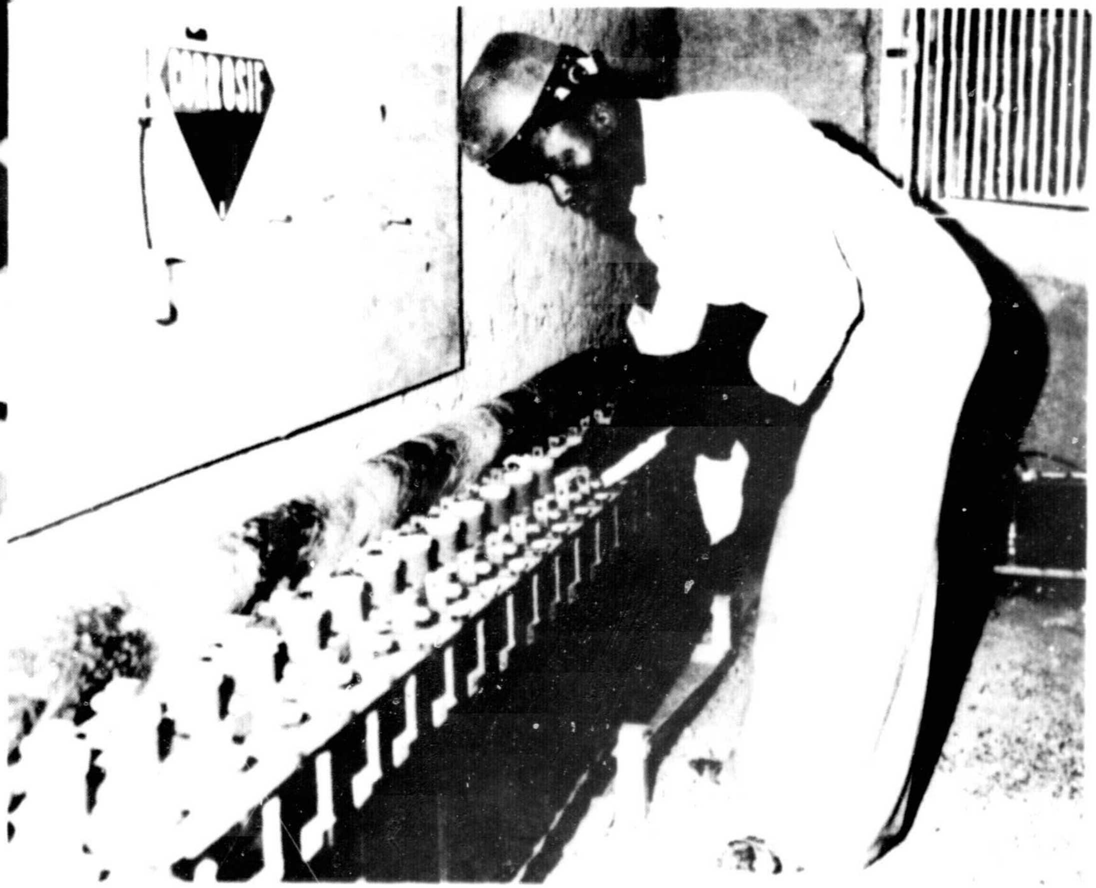

Figure 8.3-1 Inspection and Cleaning of Battery Terminals, Tangaye Village Power System

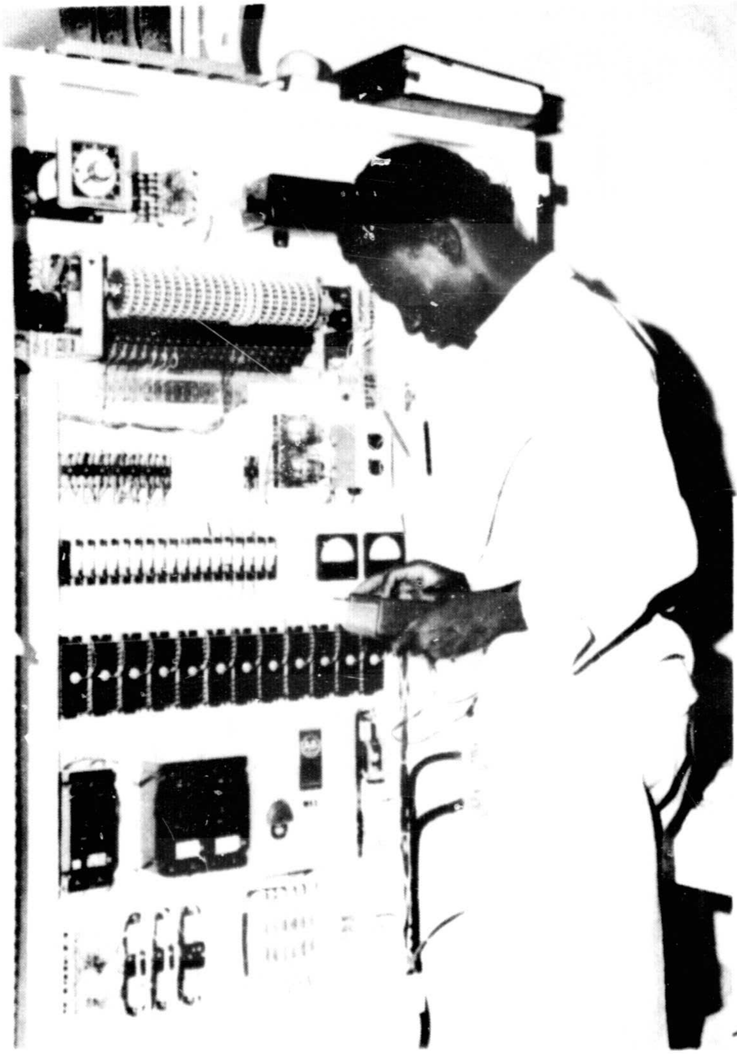

Figure 8.3-2 Routine Check of Instrumentation and Controls, Tangaye Village Power System

9.0 LOADS

9.1 Types

For purposes of discussion, loads can be classified as follows:

(1) resistive - e.g., incandescent light and heater;

(2) inductive - e.g., water pump, refrigerator, and fluorescent light;

(3) electronic - e.g., radio and TV;

9.2 Selection

The five criteria used to select loads for PV applications are as follows, in order of importance: applicability, efficiency, availability, durability, and cost.

(1) Applicability. Loads must be matched to the service required. For example, a service requirement is for 50 m^3/day of water with a lift of 5 m. In principle, it is possible to match this requirement with any of several different motor and pump combinations. Candidate motor choices may include a.c. induction, universal, or d.c. permanent magnet type, 1/3 hp or larger, depending on the flow rate requirement. Candidate pump choices may include centrifugal, axial flow, or volumetric types. The options usually will be quickly narrowed as the remaining selection criteria are applied.

(2) Efficiency. Load efficiency has a very great influence on PV system cost. The higher the efficiency of the loads the less energy will be required to perform the service and the smaller and less costly the PV system. By way of illustration of the magnitude of the effect of efficiency, let us continue the water pumping application example discussed above.

Efficiencies for various types of 1/3 hp motors and pumps operating with a 5m lift are given in Fig. 9.2-1. Within the range of pump and motor choices available, the combined efficiency of pump-motor set falls within a range of 52 percent to 16 percent. It can be estimated that in the best case a PV system of about 1.5 kWH/day output is required to supply the load and in the worst case a system of about 4.9 kWH/day (assuming negligible losses in converting d.c. to a.c.). In reality d.c. to a.c. inverter losses are significant, as discussed in section 9.5, so that in the worst case the system size will be greater than 4.9 kWh/day.

(3) Availability. The load must be an off-the-shelf item. Replacement parts must be available as well.

(4) Durability. The load must have a history of reliability, low maintenance, and ease of repairs.

(5) Cost. The cost of the load is small compared to the cost of the PV system (i.e., 10 percent or less). On the other hand, it is apparent from (2) above that load energy efficiency can markedly effect PV systems size requirements and, thereby, PV system cost. The effect of load efficiency on total cost, which may be very significant, can be shown by a cost trade-off analysis. For this purpose, let us examine a simple lighting application for one room, three hours per day. We assume a PV system cost of a 7.5 $/WH/day. Our choice of load device will be either incandescent or fluorescent lights. A 20 W fluorescent light with inverter ballast costs about $70; a 100 W incandescent light and fixture, which provides approximately the same light output (1400 lumens), costs about $10. The essential energy and cost information is summarized in the table below.

Light	WH/day	Load Cost, $	System Cost, $	Total Cost, $
Fluorescent	60	70	450	520
Incandescent	300	10	2250	2260

Fig. 9.2-1 Motor and Pump Efficiencies

Motors, 1/3 hp

Type	Efficiency, Percent
AC Induction - split phase	27-46
- 3 phase	35-50
- split capacitor	28-64
AC/DC Universal	46-51
DC Permanent Magnet	69-86

Pumps, 5m lift

Type	Efficiency, Percent
Centrifugal	~ 60
Axial Flow	~ 60
Volumetric	~ 20

The total cost (PV system plus load) is substantially less ($1740) for the fluorescent light source. Invariably, the use of the most efficient load that is available will result in the lowest total system cost.

9.3 Energy Requirements

The energy consumption of the loads determines the size of the PV system required to power the loads. Three pieces of load information are needed to calculate energy consumption: number, power, and duty cycle (usage). The load energy estimate for the PV Medical System at Ikutha, Kenya (Ref. 9-1) is given in Fig. 9.3-1, by way of illustration of the procedures.

If load requirements are not constant but vary from day to day or from month to month, it is necessary to develop a load energy profile for the entire year, so that the effect of variable demand can be factored into the calculation of system size.

9.4 Load Management

Load management involves either manipulating the number of loads in operation at any one time or the timing of their operation, with the objective of protecting the battery and improving overall system effectiveness.

(1) Load shedding. If, because of any of a number of causes (e.g., overuse, design error, lower than normal insolation or system degradation), the PV system battery approaches its DOD limit, it will be necessary to reduce the normal load demand. Failure to do so would result in damage to the battery. To prevent the battery from reaching unacceptable levels of discharge and to allow it time to recover to a higher state of charge, some of the load must be shed temporarily. This can be effected either by reducing the duty cycle or by disconnecting certain loads.

Fig. 9.3-1 Proposed Load Profile for Ikutha, Kenya

Load Device	Location	No.	Power (W)	Usage (hrs/day)	Energy (WH/day)
Fluorescent Lamp	Office	1	40	2	80
	Treatment Room	2	"	3	240
	Store Room	1	"	1	40
	Maternity Room	2	"	3	240
	Labor Room	1	"	3	120
	Family Planning	1	"	3	120
	Residences	5	"	1-1/2	300
Examination Lamp	Treatment Room	1	100	2	200
LP Sodium Vapor Lamp	Exterior	1	18	12	216
Refrigerator(1)	Office	1	86.7	14.4	1248
Sterilizer	Treatment Room	1	1200	1	1200
Two-Way Radio	Office	1	25	1	25
Discretionary - TBD					125
	Total				4154

Load shedding may be accomplished automatically or manually. In order to decide which loads to disconnect and when to disconnect them two pieces of information are needed, namely, load priority and the battery state of charge. Load priority is a matter of the perceived needs of the owner or user of the system and, therefore, must be determined on a case-by-case basis. Battery state of charge can be measured (a) by using a pilot cell technique, (b) from the open circuit voltage, (c) from the specific gravity of the electrolyte, or (d) from an accounting of the number of ampere-hours in and out. Unfortunately, none of these methods can be used with great confidence because of the uncertainty in the accuracy of the measurements. References 3-8 and 9-2 describes the operation of an automatic load shedding controller using a pilot cell technique and section 10.2 discusses experience with manual load management.

(2) Load Scheduling. In the normal course of events system effectiveness can often be improved by appropriate load scheduling. If major loads can be operated during the daylight hours rather than at night, battery size can be reduced. For example, in a water pumping application, if the amount of water required for daily needs is pumped in the daytime and stored in a dispensing tank, it can be tapped for use anytime, day or night. In effect, the water in the tank constitutes stored (potential) energy. This reduces the need for an equivalent amount of electrical energy stored in the battery that would, in the absence of the stored water, be required to power the pump during the night or under conditions of low insolation.

9.5 AC vs. DC

One of the main advantages of an a.c.-output PV system advanced by its advocates is the ease in matching system power output with commonly available load equipment. These proponents point out that there is a wide range of a.c.-powered equipment available worldwide and, further, that a.c. power allows a simple means of voltage and current transformation, comparative ease of switching and nearly constant motor speed (characteristic of a.c. induction motors).

The decision to convert the d.c. output of the array to a.c., however, should not be made without a thorough evaluation of its impact on system size and cost. The conversion of d.c. to a.c. requires an inverter--a component that increases complexity and cost and decreases overall system reliability and efficiency. In this respect the most important factor is efficiency. Inverter efficiencies generally range from about 90 percent, for operation at 100 percent of rated power capacity, to much lower values, at partial load operation. Additionally, a tare (no-load) loss, a constant parasitic power drain (5 percent - 10 percent of the rated capacity), is experienced while the inverter is operating. Lastly, when inductive loads (e.g., motors) are used, the inverter must be sized to accommodate the large, short-duration power demand on startup. Thus the use of a larger capacity inverter than would be needed to satisfy the steady state load demand results in further losses. This is because, for the same steady state operating point, the partial load efficiency of a larger inverter is less than the smaller unit. In the aggregate, these various inefficiencies can become intolerably high for small systems, for systems with a high percentage of inductive loads (e.g., motors), or for systems with relatively small power demands for extended periods (e.g., small nighttime loads).

An illustration of the impact of using a d.c.-a.c. inverter with a PV system is provided in a system cost estimate made for a PV Medical System for Pedro Vicente Maldonado, Ecuador, (Ref. 9-1). Figure 9.5-1, redrawn from the reference report, presents a plot of array and battery size, as a function of electrical load demand, for two systems--one with d.c. loads and the other a.c. loads, providing the same services. For relatively small electrical load demands (viz., 4.2 kWH/day), the a.c. system array size is 2-1/2 times larger than that for the d.c. system and, correspondingly, the battery is 2-1/2 times larger. For higher electrical load demands the size difference between the a.c. and d.c. system decreases somewhat but remains significant.

In the case of an eminently efficient load such as fluorescent light, where a.c. power is specifically required, it will often be advantageous to use a small inverter dedicated to the load, optimized for the specific load operating conditions, and that operates only when the load is on. In all other instances, the use of d.c. loads is indicated for the most energy- and cost-effective approach.

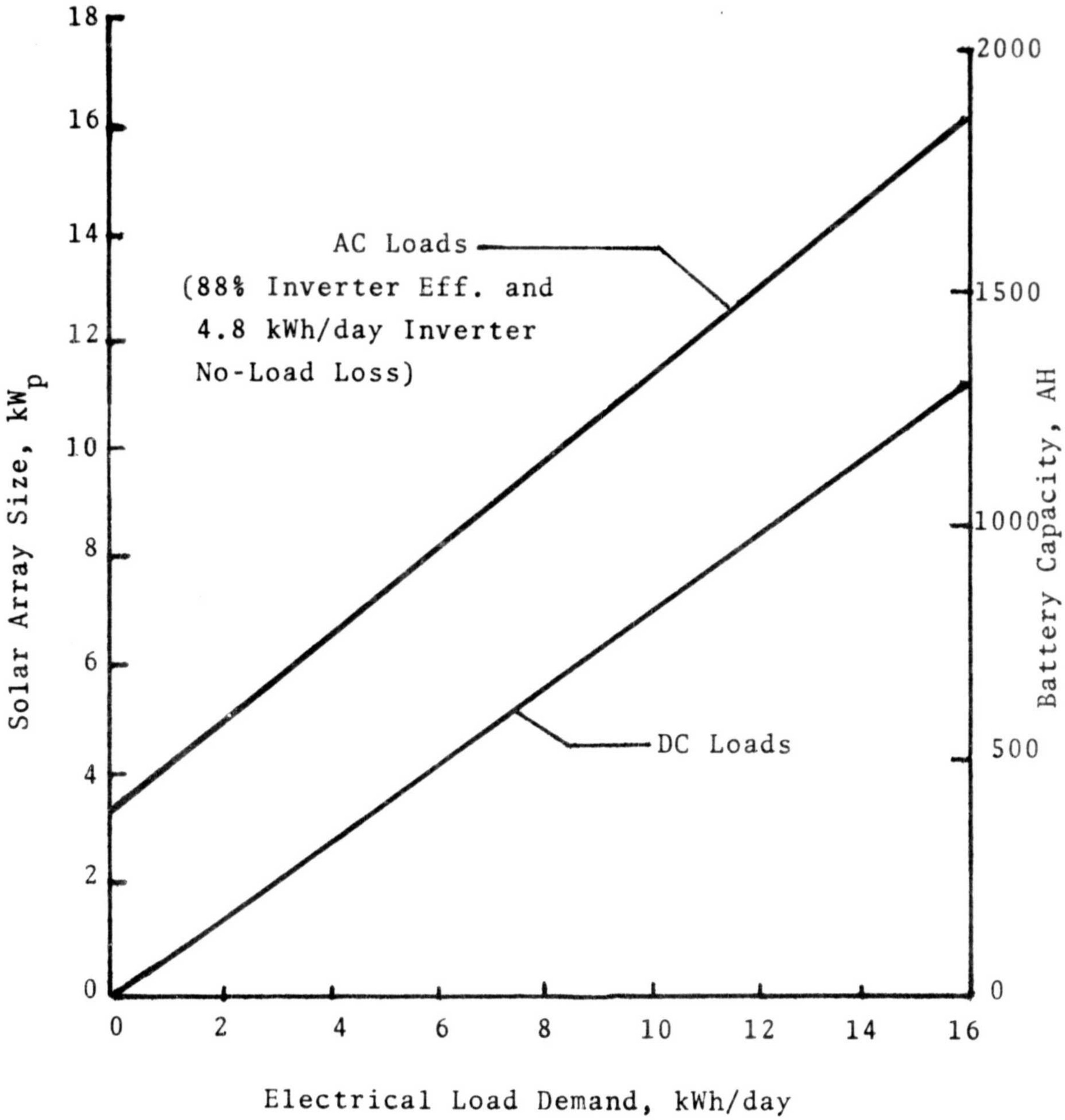

Figure 9.5-1 Illustration of the Impact of AC Loads on Estimated PV System Size for Ecuador Rural Health Delivery Demonstration Project, Pedro Vicente Maldonado

SECTION 9
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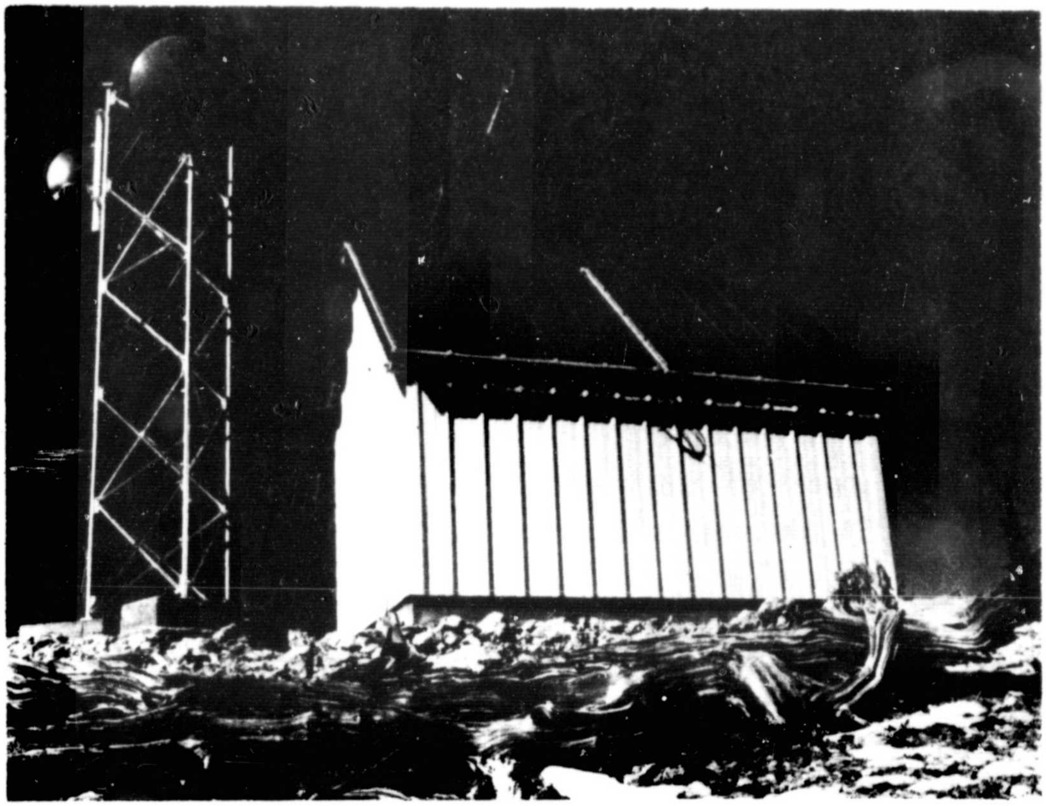
10.0 APPLICATIONS

10.1 Experience

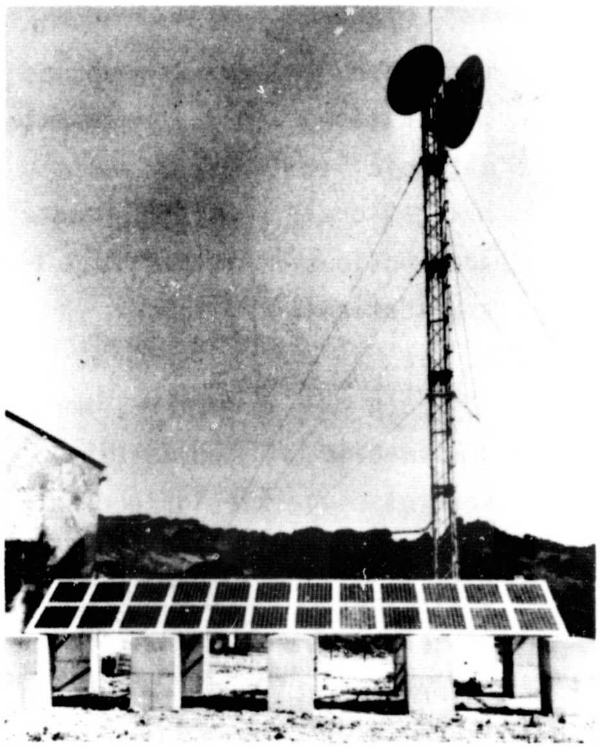
PV systems have been employed in a large number of different applications, mostly in remote and rural areas of the world, for over a decade. The state of development of applications is quite advanced, as can be judged from the sale of PV modules worldwide: cumulative sales since 1975, over 13 MW_p; 1980 sales, 4.4 MW_p; 1981 sales, 6 MW_p (Ref. 10-1). The number of PV systems represented by these figures is not known; however, assuming an average power per system of 500 W_p, we may estimate that about 26,000 PV systems were placed in operation between 1975 and the end of 1981.

The breakdown of types of applications is as follows. About 50 percent of the modules sold were used in communication applications, viz., rural telephones, emergency radio, VHF, UHF and microwave repeaters. Of the remainder, many PV modules were put to the following uses: agricultural applications (e.g., electric fences and water pumps); anti-corrosion, cathodic protection devices for bridges, pipelines and well casings; navigational aids and remote sensing instrumentation; residences; and test applications. Figures 10.1-1 to 10.1-3 provide representative photos of these applications.

In the developing world today the presence of PV applications, the combination of application types and the number of installations reflect several disparate influences: awareness of PV technology, development policy, availability of fiscal and human resources, and the interests of donor countries and organizations. By way of example, a PV application inventory for six West African countries is presented in Fig. 10.1-4.

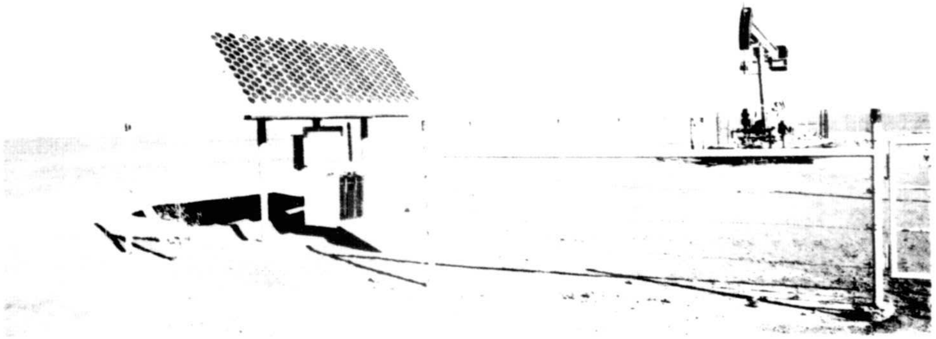


PV-Powered Communications
Relay Station, U.S.
(Courtesy of Motorola)



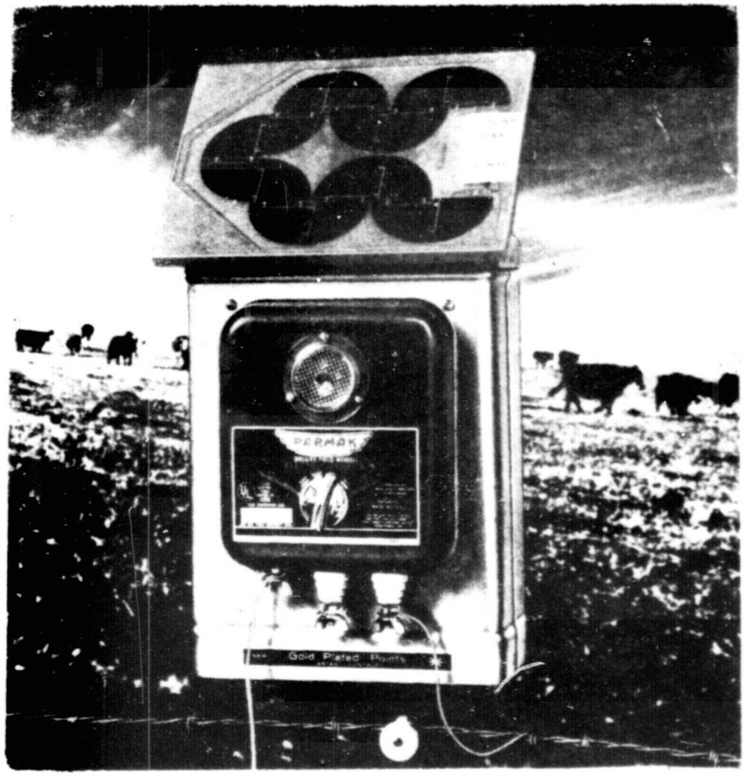
PV-Powered Microwave
Radio Repeater,
Tenerife, Canary Islands
(Courtesy of Solarex)

Figure 10.1-1 Typical Communication Applications



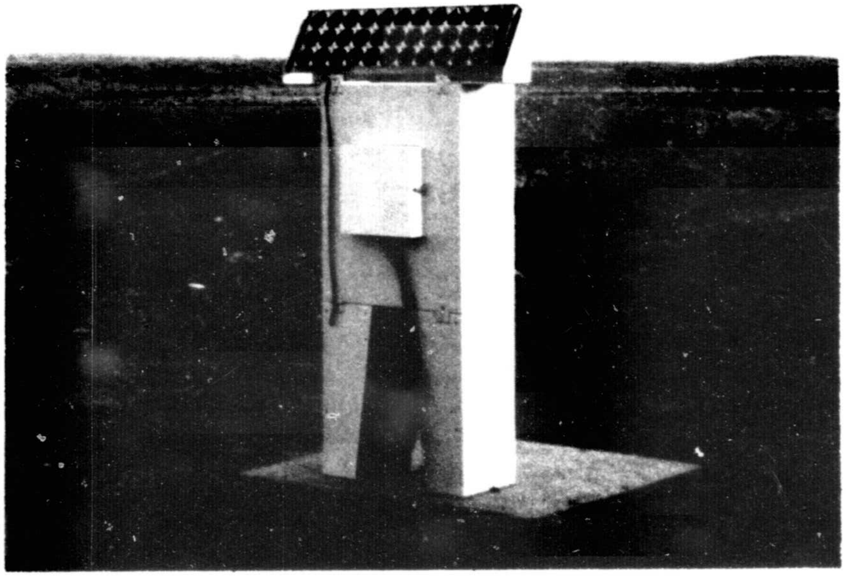
PV-Powered Oil Pipeline Corrosion Protection

(Courtesy Solar Power Corp.)



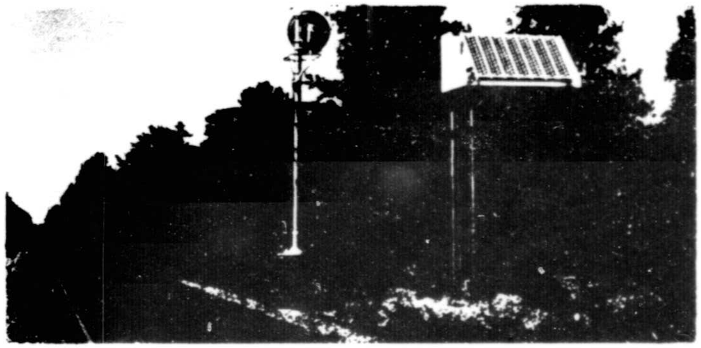
PV-Powered Electric Fencer

(Courtesy Parker McCrory Co.)



PV-Powered Remote Microclimatological Monitoring

(Courtesy Wright Associates)

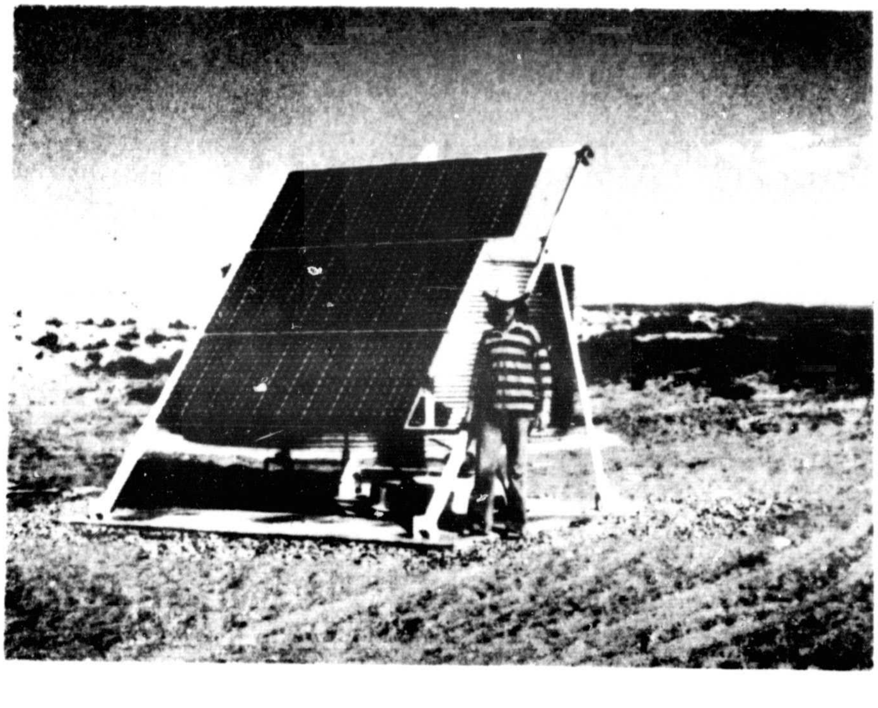


PV-Powered Railroad Signal

(Courtesy Arco Solar)

PV-Powered Drip Irrigation System, Caucaia, Ceara, Brazil

(Courtesy of Arco Solar)



PV-Powered Stock Watering System, New Mexico, U.S. (Courtesy Arco Solar)

Figure 10.1-3 Typical Water Pumping Applications

Application	Country	Number of Installations	Total Power, kWp
Domestic Water Supply	Mali	30	46.8
	Mauritania	1	0.9
	Senegal	9	13.5
	Upper Volta	5	3.5
Irrigation	Mauritania	1	3.9
Stock Watering	Upper Volta	1	0.9
R.R. Signals-Abidjan to Ouagadougou Line	Ivory Coast	29	25
Power for Hospital	Mali	2	13.5
School Lighting	Mali	2	0.3
TV Receivers	Niger	822	30
TV Repeater	Niger	1	0.12
Grain Milling	Upper Volta	1	3
Training Aid-Engineering School	Ivory Coast	1	2
	Senegal	1	0.6

Figure 10.1-4 Preliminary Inventory of PV Applications for Six West African Countries, 1977-81 (Source: Ref. 10-2)

Since 1975, the NASA Lewis Research Center (NASA-LeRC) has been responsible for the engineering development and testing of stand-alone PV applications sponsored by the U.S. government. A summary of applications placed in the field by NASA-LeRC is provided in Fig. 10.1-5; photos of selected applications are shown in Figs. 10.1-6 to 10.1-8.

10.2 Tangaye Village PV Demonstration Project

The Tangaye PV Project is selected as an illustration of recent PV application experience in a developing country setting, because it is the most completely documented activity of its kind available (Refs. 3-9, 6-1, 10-3 and 10-7).

Under U.S. Agency for International Development (AID) sponsorship, a PV system installed by the NASA-Lewis Research Center (NASA-LeRC) in the village of Tangaye, Upper Volta, began operation on March 1, 1979. The 1.8 kWp, 120 volt system, including 540 ampere-hours of battery storage, supplied DC electrical power to a commercial-type burr mill, a positive displacement water pump, and two lights in the mill building. A cooperative was formed by the villagers of Tangaye to manage the mill. About 60 village families participated in the enterprise. Fees for milling were set at parity with commercial mills in the region. Proceeds from the milling were used to pay the salaries of two full-time millers and a cashier, mill and system maintenance expenses, and the cost of the mill building construction. Profits have been used to support a number of village-wide projects and for reinvestment in other profit-making activities.

The burr mill exhibited excessive wear and was replaced by a hammer mill in September, 1979. As a result of the burr mill problems, grain was milled only 89 percent of the time from March to August, 1979. Since October, 1979, the new mill was operational 96 percent of the time, or 567 out of 591 days. The average weekly output of the mill from October 1979 through April 1981 is shown in Fig. 10.2-1. A total of 36,138 kilograms of grain were ground in

FIGURE 10.1-5 NASA LEWIS RESEARCH CENTER PHOTOVOLTAIC APPLICATION SUMMARY

APPLICATION CATEGORY	SERVICE	DATE OPERATIONAL	LOCATION	POWER, Wp	SPONSORS
REFRIGERATION	FOOD PRESERVATION	JUNE 1976	ISLE ROYALE, MI	220	USNPS/DOE
REFRIGERATION	MEDICAL	JULY 1976	SIL NAKYA, AZ	330	PHS/DOE
FIRE LOOKOUT	2-WAY RADIO, WATER, REFRIGERATOR, LIGHTING	OCTOBER 1976	PILOT PK, CA & ANTELOPE PK., CA	294 294	USFS/DOE
INSTRUMENTATION	WEATHER DATA	APR.-SEPT. 1977	NM; NY; HI; AK; MN; FL	75-150	NOAA/DOE
HIGHWAY	DUST STORM WARNING	APRIL 1977	CASA GRANDE, AZ	116	DOT-AZ/DOE
INSTRUMENTATION	INSECT SURVEY TRAPS	MAY 1977	COLLEGE STA., TX	23 and 163	USDA/DOE
REFRIGERATION	WATER COOLER	OCTOBER 1977	LONE PINE, CA	446	VARIOUS/DOE
VILLAGE: DOMESTIC AND COMMERCIAL	LIGHTS, REFRIGERATORS, WATER, WASH. AND SEW. MACHINES	DECEMBER 1978	SCHUCHULI, AZ	3600	PAPAGO TRIBE/DOE
VILLAGE: COMMUNAL AND COMMERCIAL	WATER AND GRAIN MILL	MARCH 1979	TANGAYE, UPPER VOLTA	1800	HOST COUNTRY/USAID
INSTRUMENTATION	AIR POLLUTION MONIT.	NOVEMBER 1979	LIBERTY PARK, NY	360	NJ-DEP/DOE
INSTRUMENTATION	SEISMIC MONITORS	JANUARY 1980	KILAUEA VOLCANO, HI	18	USGS/DOE
HEALTH: IMMUNIZATION	VACCINE REFRIGERATOR/FREEZER	OCT. 1982-1983	COLUMBIA, GAMBIA, MALDIVE IS., INDIA, IVORY COAST, PERU	210-330	CDC/DOE
			ZAIRE, ZIMBABWE, LIBERIA, UPPER VOLTA, BANGLADESH INDONESIA, TUNISIA, EGYPT, MOROCCO, GUYANA, ECUADOR, DOMINICAN REPUBLIC, HONDURAS, HAITI, GUATEMALA, TOGO, PAKISTAN		HOST COUNTRY/USAID
VILLAGE: DOMESTIC, COMMUNAL, COMMERCIAL AGRICULTURE	WATER, LIGHTING, AND APPLIANCES DRIP IRRIGATION	NOVEMBER 1982	HAMMAM BIADHA, TUNISIA	27000 3400	HOST COUNTRY/USAID
HEALTH: MEDICAL POSTS	LIGHTS, REFRIGERATOR, STERILIZER, ETC.	SEPTEMBER 1982 - JANUARY 1983	GUYANA, ECUADOR, KENYA ZIMBABWE	1500-300	HOST COUNTRY/USAID
VILLAGE: COMMUNAL	DISPENSARY - LIGHTS AND REFRIGERATOR SCHOOL - LIGHTS AND TEACHING AIDS WATER SUPPLY AREA LIGHTING	JULY 1983	4 VILLAGES, GABON: NYALI, DONGUILA, BOLOSSOVILLE, BOUGANDJI	TBD	HOST COUNTRY/DOE
COMMUNICATIONS	SATELLITE-REMOTE EARTH STATION	1983	TBD	2000	HOST COUNTRY/USAID

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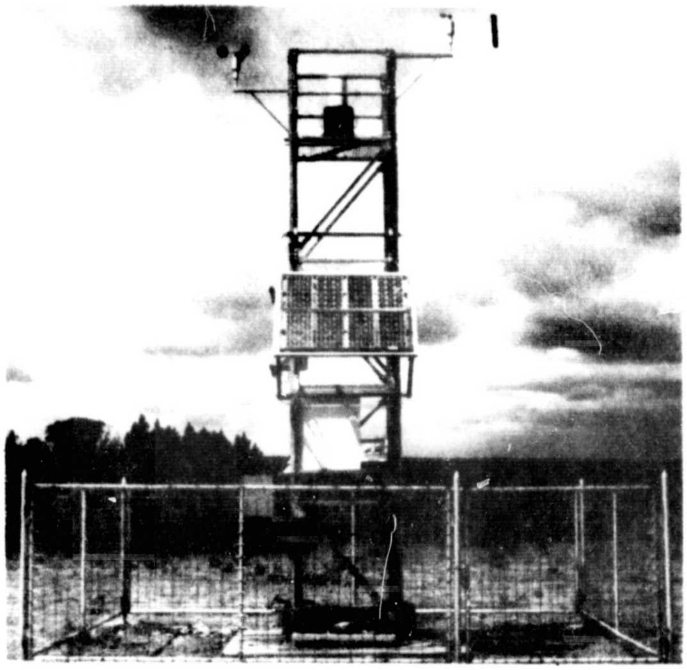
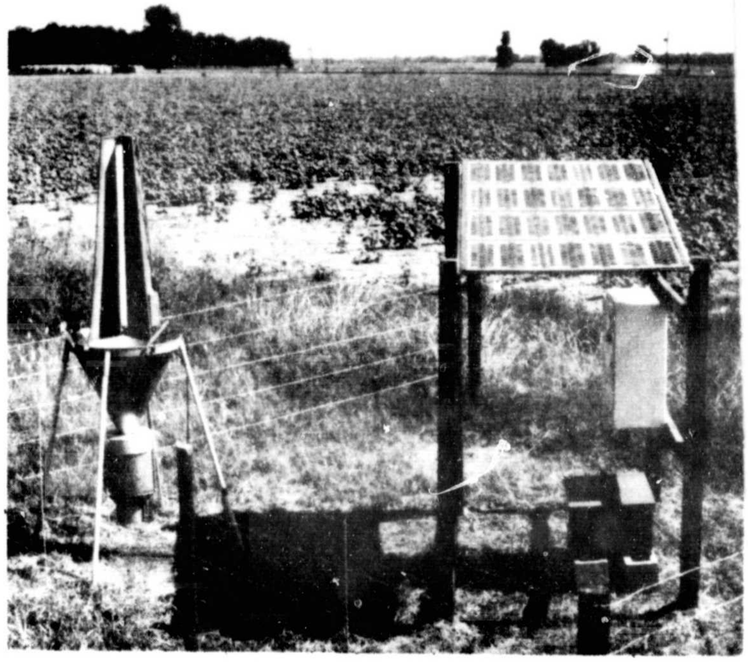


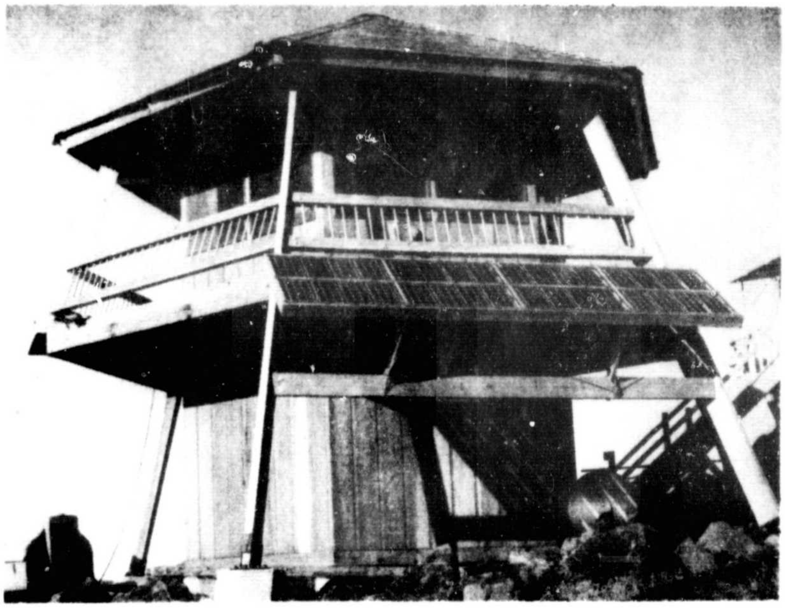
PV-Powered Remote Weather Station

New Mexico, U.S.



PV-Powered Insect Survey Trap

Texas, U.S.



PV-Powered Fire Lookout

California, U.S.

PV-Powered Refrigerator

Sil Nakya, Arizona, U.S.

Figure 10.1-6 Selected PV Applications- NASA Lewis Research Center

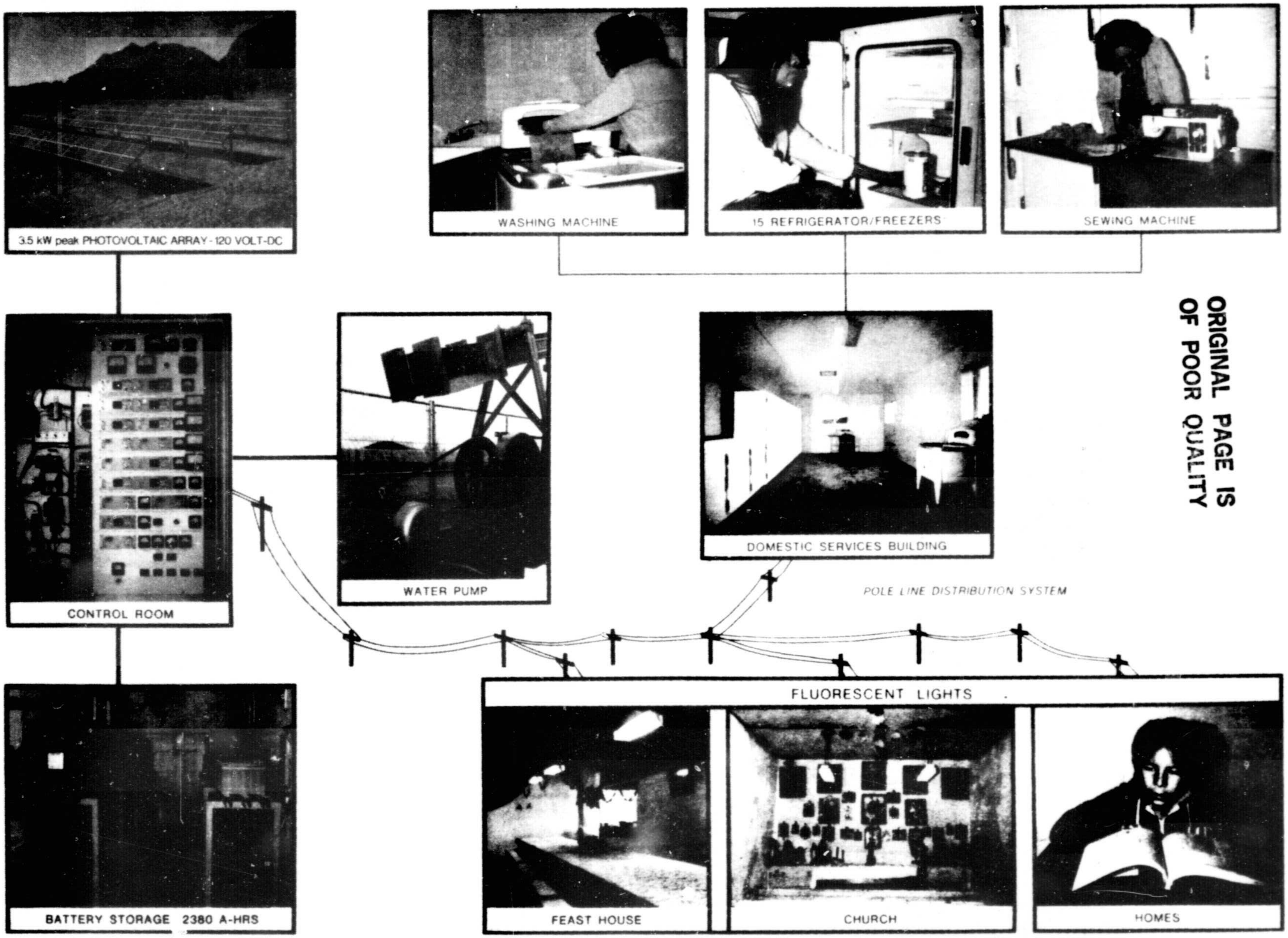


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Figure 10.1-7 WORLD'S FIRST VILLAGE PHOTOVOLTAIC POWER SYSTEM - PAPAGO INDIAN VILLAGE OF SCHUCHULI, ARIZONA

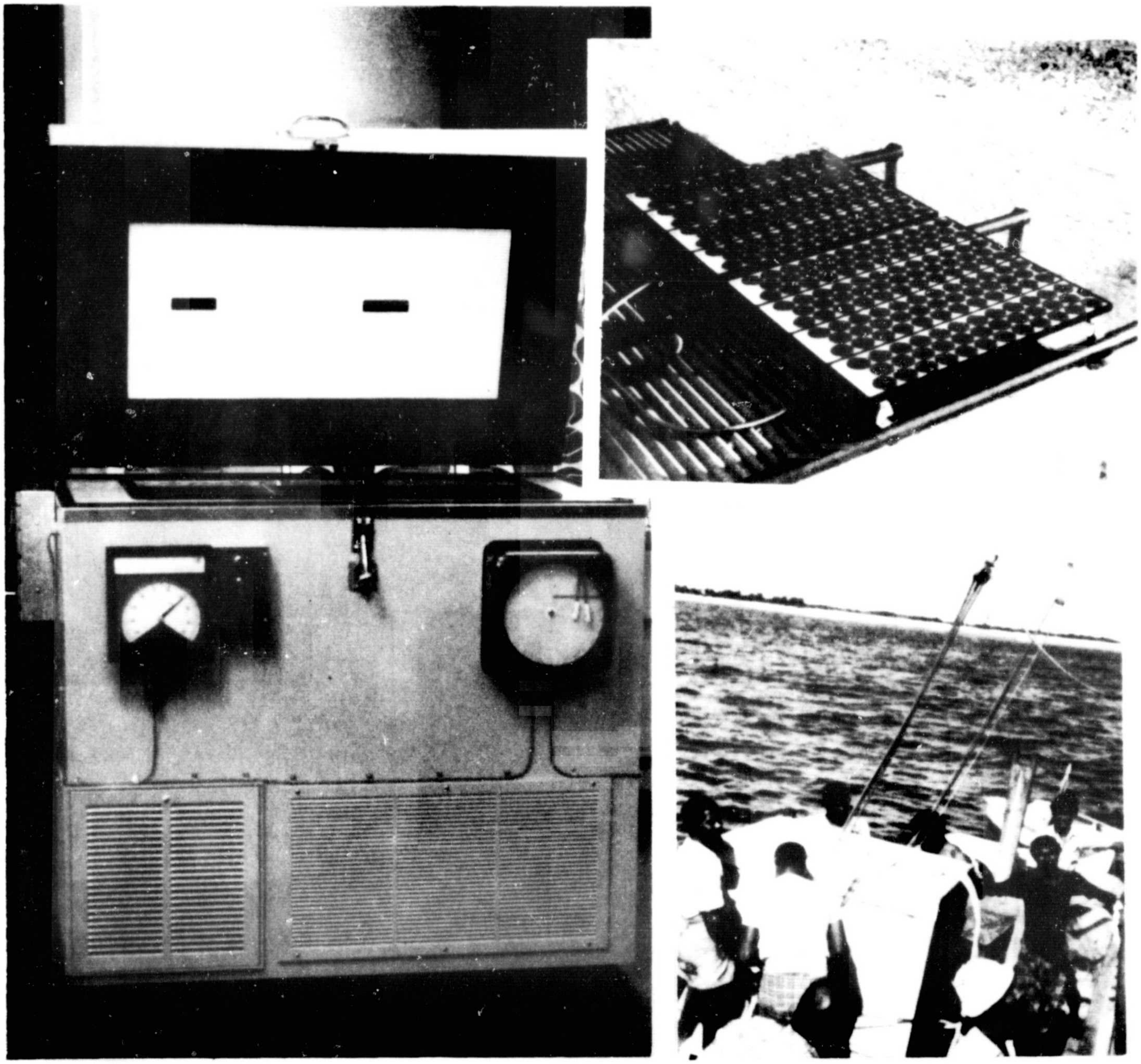

Figure 10.1-8 PV Vaccine Refrigerato/Freezer Unit, Delivered and Installed at Kulu Duffushi, Maldive Islands, April 1982

about 1000 hours. A cyclic trend in customer patronage of the mill is apparent. Usage increased during the harvest season (October-November), peaked in the months following, then dropped due to depletion of grain stocks and intensive agricultural activities away from the Village center.

Water is pumped from a well near the mill building to a nearby storage tank equipped with taps. Water is available to everyone. A summary of the water pumping data is given in Fig. 10.2-2. Water consumption follows a seasonal pattern, the maximum use occurring at the height of the dry season, March to April. The total amount of water pumped as of October 12, 1980, was 4,623,000 liters for over 3700 hours of pumping.

About 7 months after installation, failures began to show up in the Solarex 9200J solar cell modules; from that time on, failure of modules continued at about a rate of 2 percent per month, on the average. The failures were analyzed and identified as having resulted from thermal-stress induced, fatigue cracking of the cell electrical interconnects. Replacement modules were provided by NASA and they were installed beginning September 1980, by personnel from the Voltaic Direction de l'Hydraulique et de l'Equipement Rural (HER) or from NASA, with the assistance of resident AID personnel.

System operation continued uninterrupted in spite of cumulative module failures. The most significant effect on system performance was a progressive diminution of overall system energy output as failures accumulated. Full system output was restored on replacement of the failed modules. As can be seen in Fig. 10.2-2, water pumping was unaffected by the module failures. In fact, water use increased somewhat during this period. On the other hand, the grain mill operation (Fig. 10.2-1), had to be curtailed The overall cutback was about 25 percent, roughly corresponding to the cumulative percentage of module failures. The millers decided the specific amount of daily cutbacks needed, based upon meter readings of the total daily energy generation and consumption. This load management procedure was highly successful in two

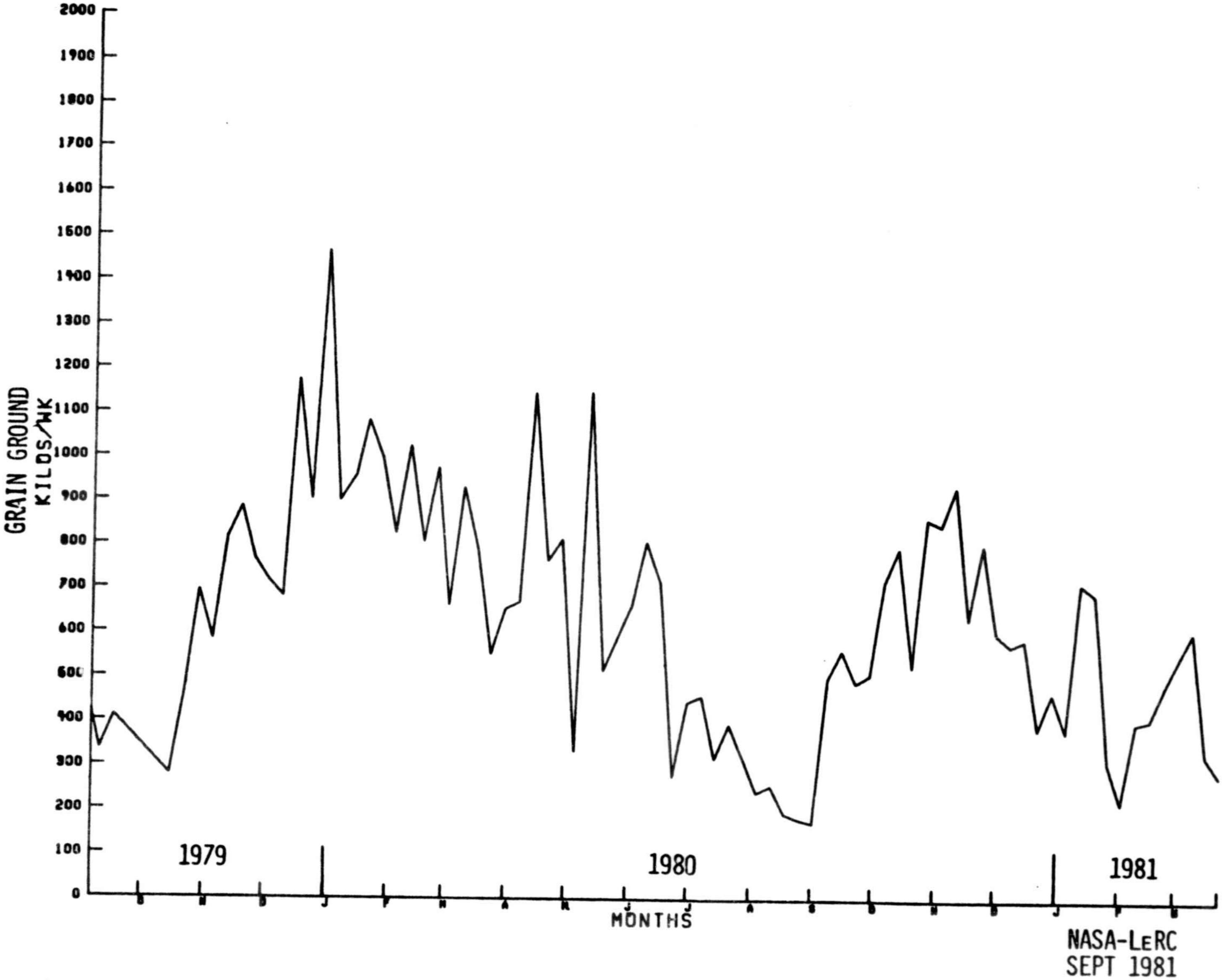

Figure 10.2-1 Tangaye PV System Mill Use

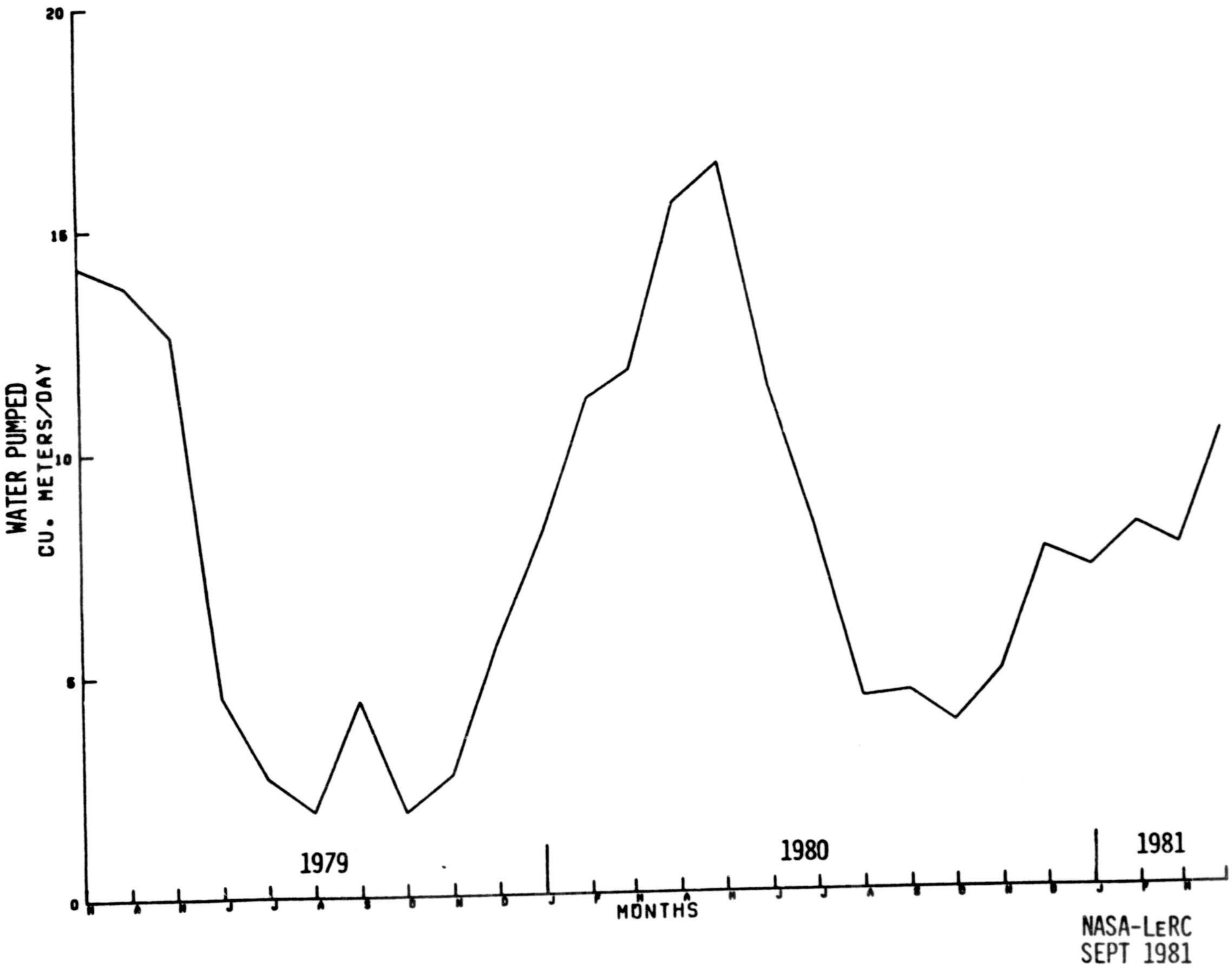

Figure 10.2-2 Tangaye PV System Water Use

respects: (1) it enabled the system to operate near its maximum potential, until repairs could be made, without draining the battery to an unacceptable low level of discharge; and (2) it provided a demonstration of the ability of relatively untrained personnel to manage the power flow of a large PV system.

Because of the success of the Tangaye Project, villagers requested, through AID, that the capacity of the mill be increased. With the cooperation of the U.S. Department of Energy (DOE) and NASA, this request was approved by AID. During May 1981, the Tangaye PV system was refurbished and enlarged to twice its original capacity. All remaining original modules were removed and 3.6 kW_p of new modules of a manufacture and make of demonstrated reliability were installed. This, the first time that a large, operating PV system was expanded substantially in energy capacity, highlights the inherent modularity of PV systems, which permits system growth with growth of user's needs.

After the system was enlarged new loads were added: three 20 W fluorescent interior lights, an 18 W sodium vapor exterior light, and a small refrigerator unit. With the lights, night classes can be conducted in adult literacy. The system was turned over to the Government of Upper Volta on May 18, 1981, who assumed responsibility for monitoring and repair. Village personnel will maintain the system as before. Fig. 10.2-3 is a photograph of the present system. From left to right, the water dispensing tank, the mill building, with the well and pump in front, the guest house behind the mill building, and the PV array field and security fence are shown.

10.3 Future Trends

10.3.1 Near Term

In places having no available or dependable electrical power, it is desirable that an electrical product be packaged with its own power supply.

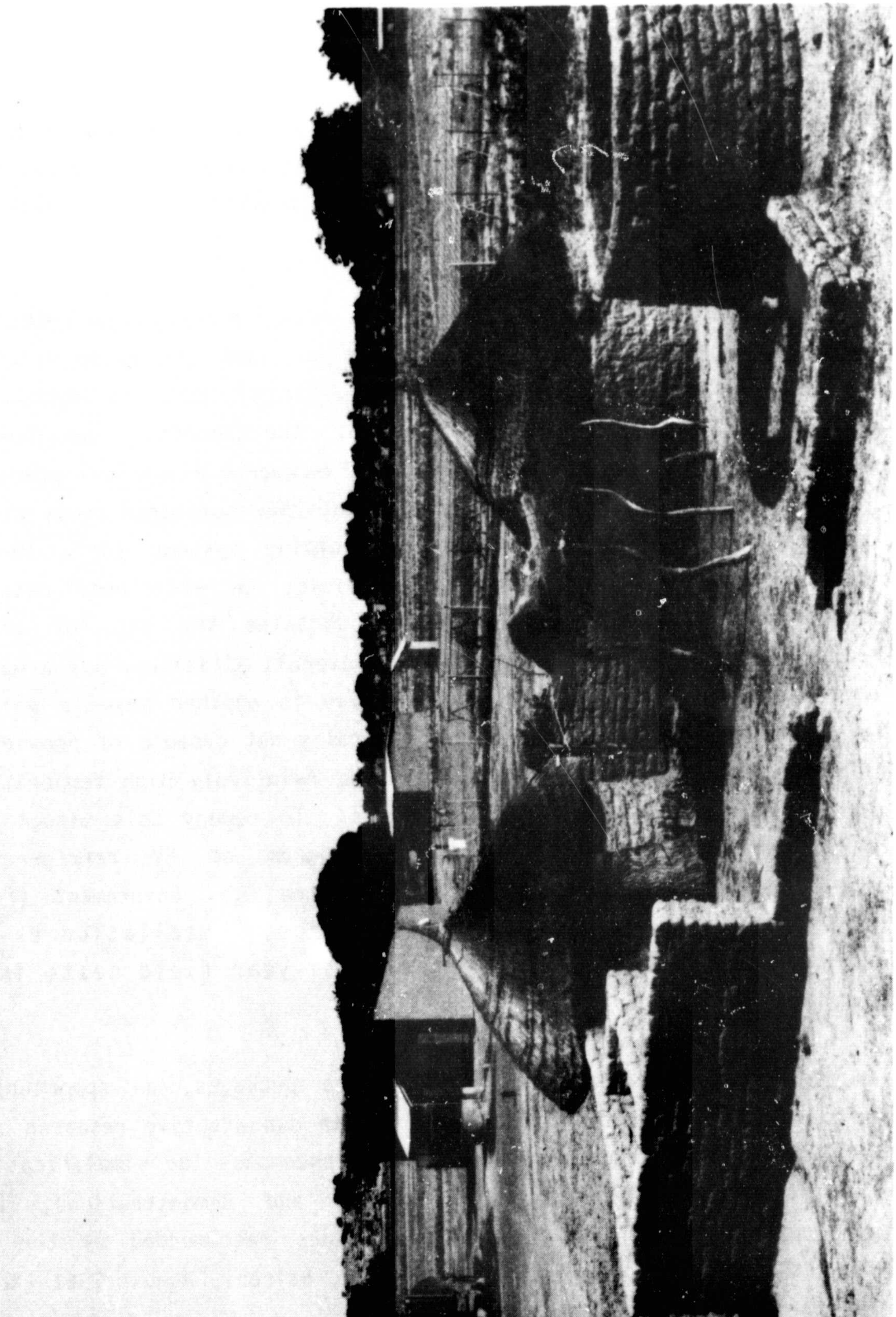

Figure 10.2-3 Overview of PV Power System and Facilities at Tangaye, Upper Volta

A well-known, highly successful product of this type is the battery operated transistor radio. It seems likely that over the next ten years PV application development will be closely linked to discrete product (service package) development.

PV service packages most relevant to rural needs in developing countries are (1) water pumps (potable water - 10 to 20 m^3/day and irrigation - 50 to 100 m^3/day), (2) lights (20 to 40 W fluorescent), (3) refrigerators (medical - 100 liter capacity), and (4) radio communication. The commercial development of reliable, energy efficient, and minimum cost PV-powered electrical products is still in an early stage. For example, a recent UNDP sponsored study of 11 commercial small-scale PV-powered irrigation pumping systems (Ref. 10-4), concluded that "there is considerable variability in efficiency between different systems and since the efficiency dictates the size of array necessary for output, and array costs dominate, overall efficiency has a major effect on equivalent annual cost." Refrigeration is another case in point. Commercial electric refrigerator units are generally not capable of providing energy-efficient and dependable operation in the relatively high temperature environments found in many developing countries. To remedy this situation, specifically for vaccine preservation, a program of PV refrigerator development and testing has been sponsored by the U.S. Government (Fig. 10.1-5). Ref. 10-8 provides **system description, installation experience, and performance data for the multi-year field tests in 24 developing countries.**

With respect to development of PV service packages, an opportunity exists for developing countries to carry out their own adaptive research and development. Such research and development could encompass the simplification of hardware, selection of components, tests and demonstrations, and manufacture and assembly, along the general lines recommended by the UN Conference on New and Renewable Sources of Energy, Nairobi, August 1981 (Ref. 10-6).

10.3.2 Far Term

In about ten to fifteen years, it is likely that we will see the growth of a substantial number of PV applications associated with bulk electrical generation in the range of 50 to 200 MWH/year--enough to satisfy the electrical requirements of small communities or cities. At present, for this level of bulk electrical generation the dominant power system is the diesel generator. The penetration of PV systems into the bulk energy diesel generator market depends upon reductions in PV energy cost between now and the late 1990's.

SECTION 10
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11.0 SERVICE PEFORMANCE

In preparing design and cost estimates, one important, though often overlooked, consideration is the quality of service that the system is to deliver. For any electrical power system, the common indices of service performance are reliability, availability, and voltage control.

11.1 Reliability

Reliability is the probability that an item--a part, a component, an assembly, a unit or an entire system--will perform its intended function, for the intended period of time, under stated conditions. Conversely, the probability that an item will fail in a specified period is simply 1 minus reliability. Reliability, therefore, provides a measure of how often service is likely to be interrupted (i.e., experience an outage), due to a critical failure.

A useful measure of power system reliability is the forced outage rate, **f**, which is defined as follows:

$$\mathbf{f} = \frac{\text{Forced Outage Time}}{\text{Forced Outage Time + Service Time}}$$

where

Forced Outage Time = Time, in hours or days, during which the system (or major subsystem) was unavailable due to having been forced out of service

Service Time = Total hours or days that the system (or major subsystem) was actually in operation and providing power.

11.2 Availability

Availability is a measure of the duration of loss of service. It is defined as the fraction of time that a system (or subsystem) is neither forced out of service nor is otherwise out of service because of scheduled or unscheduled maintenance. The annual availability, A, for a power system is given by the following general equation:

$$A = (1 - F)(1 - M) \tag{1}$$

where

F = Total forced outage time per year

M = Total maintenance down-time per year (i.e., the time out of service due to maintenance)

To illustrate, we can calculate the annual availability for two conventional electrical power subsystems for which outage and maintenance data are available (Ref. 11-1):

Subsystem	F	M
Fossil Fuel-Generator Unit	5.3 percent	9.9 percent
Nuclear-Generator Unit	11 percent	13 percent

For the Fossil Fuel unit,

$$A_F = (1 - 5.3/100)(1 - 9.9/100) = 0.85$$

For the Nuclear unit,

$$A_N = (1 - 11/100)(1 - 13/100) = 0.77$$

It should be remembered that these subsystems are elements of a larger central station-grid system. A total system generally consists of several generator units linked to transmission and distribution subsystems. The overall availability for central station-grid systems will be discussed in section 11.4.

For PV systems, it is helpful to separate the forced outage term (F) into it two components: F_C, the forced outage rate due to component failure, and F_I, the forced outage rate due to lack of adequate solar insolation. The latter term is a function of the probability distribution of solar energy at the site, array and battery size, and the load requirement. The annual availability for a PV system (A_{PV}) is

$$A_{PV} = (1 - F_I)(1 - F_C)(1 - M) \tag{2}$$

Estimates of F_I can be made, using a method based on probability mathematics described in Ref. 3-11. Loss of energy probability (LOEP) used in Ref. 3-11 is equivalent to F_I. These terms will be used interchangably here.

F_C is a function of frequency of failure and the down-time required for repairs. The down-time includes the travel time needed to reach the site, the time to locate and identify the problem, the time to obtain necessary replacement parts (if spares are not on hand), and the time to replace parts and correct faults. For a system at a remote location, repair down-time may have a significant effect on F_C. Strategies for minimizing F_C involve (1) increasing reliability of system components (by means of selection, burn-in, qualification testing and redundancy) and (2) stocking critical replacement parts on-site.

Maintenance down-time, M, for a PV system is usually negligible. Most maintenance functions can be performed on the system without interrupting power to the loads.

11.3 Voltage Control

Another basic index of service performance is voltage control. The electrical power entering a user's service area must be controlled, so that voltage is within suitable limits for utilization by the loads. Most loads will only operate satisfactorily, or at all, within a relatively narrow voltage range. Generally, voltage control to ±10 percent of nominal voltage is considered desirable.

11.4 Comparison of Electrical Systems

In this section we will attempt to compare known service performance of PV stand-alone systems with that of competitor systems, namely, central station electric grid and diesel generator. Furthermore, for purposes of PV system sizing and cost estimation (section 13), the historical service performance of competitor systems will serve as a benchmark, or guide, in setting practical system requirements. Displayed in Fig. 11.3-1 are pertinent service performance data gleaned from various sources. As can be noted, information on history of service performance of electrical systems is scanty.

11.4.1 Central Station Electric Grid

Rural or remote area customers usually receive the poorest service from the electric grid, in comparison to urban or industrial customers. Inferior service may be due to any or a combination of factors among which are (1) longer and more difficult to service distribution lines, (2) lower assigned priority in event of system overload, and (3) paucity of trained maintenance and service personnel. Although, the Basaisa and Amristar values (Fig. 11.3-1) were the only quantatative data that could be obtained, corroborating anecdotal information abounds on the poor service availability of the electrical grid in rural areas of developing countries. Two accounts from Ref. 11-10 concerning grid service in rural India are quoted below.

Figure 11.3-1 SERVICE PERFORMANCE OF ELECTRIC SYSTEMS

System Type	Service Area	Average Availability	Voltage Control, percent	Refs.
Central Station Electric Grid	United States-Urban/Rural	0.9998	±5	11-2
	Pakistan-Urban	0.99	±25	11-3/11-4
	Tunisia-Urban	0.99		11-5
	Basaisa, Egypt-Rural	0.74		11-6
	Amristar, India-Rural	0.75		11-7
Diesel Generator Stand-Alone 5-15 kW		0.95	±5	11-8
PV Stand-Alone	United States - Remote	0.97	±10	11-9

One account from Karnataka State observes that, "many farmers with electric pumpsets also have stand-by diesel pumpsets because of power cuts and unreliability of power supply." A second account from the Ludhiana District of the Punjab, where all villages are electrified, reports that "the number of electric motors for water lifting increased from 11051 in 1969-70 to 15322 in 1974-75 and 19497 in 1975-6, while the number of diesel engines (for stationary and mobile use) increased from 24206 to 42070 to 43769 over the same period. Many farmers have both because of the unreliability of electric supply."

In urban areas of developing countries, it may be that grid electric power availability is about 0.99, as indicated by the limited data (Fig. 11.3-1); nevertheless, the presence of back-up diesel generators in hotels and public buildings would argue that availability is in reality much less than 0.99. Even in urban locales with supposedly good availability from the electric grid, the quality of service may be degraded due to inadequate voltage control. Large voltage excursions in the grid electrical supply result in damage to, or non-operability of, user's equipment and appliances. Service voltage reduction, or "brown out," is commonly practiced by utility companies to reduce load on the system, in order to accommodate deficiencies, temporary or permanent, in generation, transmission and/or distribution. "We have weak electricity in our city," commented a doctor in an Egyptian urban health clinic to the author, explaining why their new refrigerator was not operating.

11.4.2 Diesel Generator

The diesel stand-alone system values given in Fig. 11.3-1 are based on U.S. military specifications for 5-15 kW diesels. In this instance, the availability value represents ideal values achieved by diesel units that are provided with a high level of maintenance, trained personnel, and spare parts. Stand-alone diesels in a less structured setting--the more common situation--can be expected to exhibit higher forced outage rates and

consequently lower availability. Furthermore, even if the diesel equipment is in operating condition, it may be operated only a few hours each day. Such scheduling is common for rural and small-city electric service and results in extremely low service availability.

11.4.3 Photovoltaic Stand-Alone

The PV stand-alone system service performance, indicated in Fig. 11.3-1, represents 14 first-of-a-kind systems that were placed in operation in remote locations at various times between 1976-80 and have accumulated a total of 484 months of service time. Down-time experienced was the result of 7 outages among 5 of the 14 systems. The designs of these systems yielded a predicted F_I (or annual LOEP) of 0.1 percent or less. Thus, the observed availability of 0.97 is entirely due to component failure outages (F_C), since M was found to be 0. This, in fact, is consistent with the data. The outage causes (and numbers) were as follows: regulator failures (2); controller failures (2); user negligence (2); and defective load appliance (1).

Because of the circuit redundancy that can be designed into PV arrays, module failures, when they do occur, seldom result in a total system outage (see section 3.2.5). Even in the extreme case, where cumulative module failures reached 30 percent, the system experienced no down-time; rather, there was a cumulative reduction in total energy delivered by the array. This type of gradual reduction (over several months) in energy output requires either temporary, partial load-shedding or a reduction in hours of operation until the failed modules can be replaced.

There is every reason, especially financial, to avoid overdesign (i.e., oversizing,) of PV systems. System design should be targeted to match or better the service availability provided by competitor systems. In the near term, when most applications will be in rural and remote areas, this availability target (based upon the discussion in sections 11.4-1 and 11.4-2) is in the range of 75 percent to 95 percent. Taking the upper limit, and assuming F_C = 3 percent (**Fig. 11.3-1**), we may infer that a PV system designed to a 2 percent annual LOEP will provide equal, and probably better, service than competitor systems.

SECTION 11
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12.0 SYSTEM PRELIMINARY SIZING

The purpose of this section is to acquaint the reader with a method for the rapid estimation of system size (i.e., array area or power) and battery capacity for a specified load requirement, for a given site, and for a desired level of service availability. The method is simple and useful: simple because it requires only three input values; useful because array and battery trade-offs--the substance of system cost optimization--can be made readily. The three input values are (1) the average of the daily insolation for worst month of the year, (2) the overall system efficiency, and (3) the average daily load. Since the procedure for estimating the average daily load was covered in section 9.3, only items (1) and (2) are discussed below.

12.1 Average Daily Insolation

12.1.1 Description

Key terms used in the following discussion are defined below.

Irradiance -- The radiant power incident upon a unit area of surface. Units: W/m^2

Irradiation -- The radiant energy received by a unit area of surface during a given time period. Units: kWH/m^2-day.

Insolation -- Solar irradiation. Units: kWH/m^2-day.

The amount of sunlight reaching a collector on the surface of the earth is influenced by several factors. Just outside the atmosphere, the radiant power (irradiance) of sunlight on an area that is oriented perpendicular to the solar rays is relatively constant throughout the year (1.36 kW/m^2 ± 3 percent); minor variation is due to changes in earth-sun distance over the earth's orbit. However, the solar irradiance on an extraterrestrial area

The Earth, a seasoned traveller...

Once a year, the earth makes a full orbit around the sun, permitting its inhabitants to experience winter, spring, summer and fall.

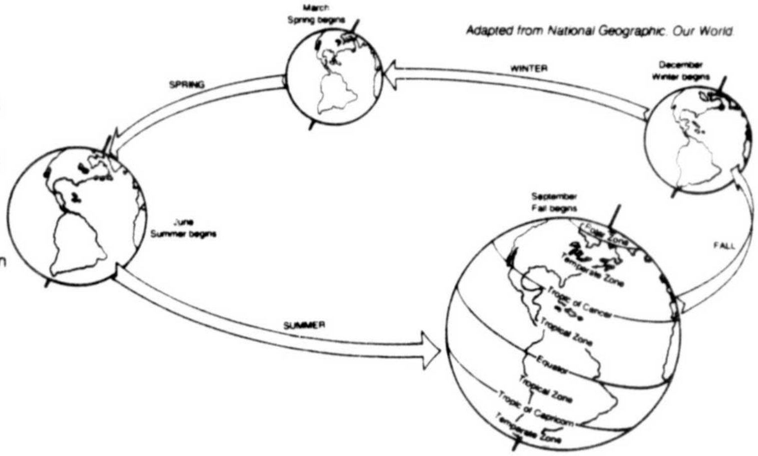
These seasons occur because the earth tilts to one side (of an imaginary vertical axis) at an angle of 23½ degrees as it revolves around the sun. Without that tilt, there would be no seasons. Night and day would be 12 hours long everywhere, all of the time.

To see why this is so, imagine the earth's orbit as the edge of an oval table with the sun in the center.

In winter, the northern hemisphere is tilted away from the sun, while the southern hemisphere is tilted towards it. This means very different weather for the two hemispheres.

In the northern half of the world, much less sunlight is available each day to warm the land and oceans. Sunlight strikes at an angle, causing less heat to be collected.

The sun, incidentally, does not radiate energy in the form of heat. It generates sunlight that only produces heat when it strikes something it can't go through, such as a metal roof or a sunbathing cat.



The longest day of winter in the northern hemisphere—the winter solstice—occurs around December 21. The sun crosses the sky at its lowest point in the horizon. It is not even visible above the Arctic Circle.

Meanwhile, the southern hemisphere experiences its hottest weather. The sun is highest in the sky on December 21, providing the longest day of the year. Sunlight strikes the land and water from almost directly overhead, causing molecules to heat up more rapidly. This is why it can be sweltering in Australia while icy cold in Alaska.

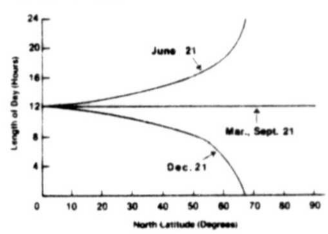
Six months later, the situation is reversed. Around June 21, the northern hemisphere experiences its summer solstice—the longest day of the year. The southern hemisphere has its cold, dark weather in June.

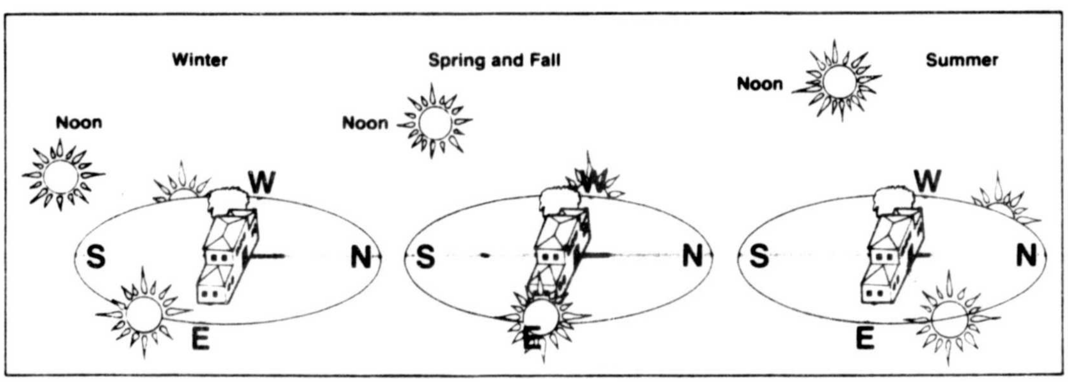
As it journies around the sun, the earth also marks the passage of spring and fall. These occur half way between each solstice and are called the spring equinox and fall equinox. At this time of year, everything is equalized. Night and day are the same length all over the earth.

While daylight and seasons vary in much of the northern and southern hemisphere, in the tropics—a wide belt of the earth near the Equator—the sun travels the same path almost every day. Hence, night and day vary little in length and the weather is warm all year.

At the north and south poles, of course, the sun's angle is always very low. Frigid temperatures and ice caps are a permanent condition.

Length of day as a function of latitude





Position of sun at sunrise, noon and sunset in middle northern latitudes at beginning of each season

Figure 12.1-1 Seasonal Changes of Solar Irradiance (Source: Ref. 12-5)

horizontal to the earth (at any location) varies considerably throughout the year. Because the earth's axis is tilted at an angle of 23.5° relative to the plane of its orbit about the sun, the solar irradiance on a horizontal extraterrestrial area will depend on latitude and day of the year (see Fig. 12.1-1, from Ref. 12-5).

Sunlight traveling through the upper atmosphere is attenuated as a result of absorption by water vapor and gases and scattering by atoms, molecules and particulate matter. Ten percent or more of the solar irradiance is lost. In the lower atmosphere, solar irradiance is attenuated further by cloud cover. Over all, cloud cover is the greatest single factor in determining the amount of solar irradiance that reaches a collector on the surface of the earth.

The angle at which a collector is oriented relative to the sun's rays will affect the amount of radiation it intercepts. The surface of a fixed position collector is commonly tilted from the horizontal to an angle approximately equal to the latitude angle. Alternately, to increase the amount of solar radiant energy (irradiation) received during the winter months (or whatever the period of lowest irradiation) the collector can be set at an angle that is more nearly perpendicular to the sun's rays. Improvement can be realized in the amount of irradiation collected annually if the tilt angle of the collector is adjusted once or more during the year. Whether or not the gain achieved is significant depends upon site and application.

12.1.2 Data

Average daily solar irradiation (insolation) for a specific site may be obtained (1) from existing solar radiation, sunshine duration, or cloud cover measurements; (2) by interpolation of data of bracketing locations; or (3) by assuming that data from similar sites elsewhere are applicable. For a site in a rural area of a developing country, it will be rare to find existing solar insolation measurement data; invariably method (2) or (3) will have to be

employed to provide estimates. Since insolation is relatively uniform over large portions of many countries, the interpolation technique (method 2), if data can be found, should be satisfactory for purposes of preliminary design. Exceptions to this generalization are regions with large microclimate variability. In such regions high mountains or other local geographical conditions cause substantial variation in cloud cover or atmospheric clarity between points from several to a few hundred miles apart. Method 3 is a stop-gap approach.

Ref. 12-1 contains world maps with isolines of total solar irradiation on a horizontal surface, in units of langleys per day, for each month of the year. For the convenience of the reader these maps are reproduced in Appendix G. A listing of data regarding average daily insolation on a horizontal surface, by month, for approximately 900 sites worldwide can also be found in Ref. 12-1 in units of langleys per day. Ref. 3-11 lists the data for the same sites except they are in units of K_H (the ratio of average daily insolation on a horizontal surface to the average daily insolation on an extraterrestrial horizontal surface). A compilation of current data can be found in Ref. 12-2, the World Network Irradiation Balance Data, sponsored by the World Meteorological Organization. These data, from cooperating stations around the world, are published in monthly issues containing tabulations of average daily insolation on a horizontal surface, for each day of the month, in units of langleys per day.

The procedure for calculating the average daily insolation on a tilted surface for any month of the year, based on a method proposed by Liu and Jordan (Ref. 12-3), is given in Ref. 3-11. Ref. 3-11 also includes instructions for relevant programming of the TI-59 or the HP-67 calculators. For the convenience of the reader, listings of monthly values of average daily insolation at various tilt angles for 8 selected sites can be found in Appendix H.

Several systems of units for average daily insolation are in use:

$$1 \text{ kWH/m}^2\text{-day} \; = \; 86.0 \text{ langleys/day} \; = \; 86.0 \text{ gm cal/cm}^2\text{-day} \; = \; 3.6 \times 10^6 \text{ Joules/m}^2\text{-day}$$

For purposes of uniformity and to minimize confusion, insolation in units of kWH/m^2-day will be used here.

12.1.3 Worst-Month Average Daily Insolation

The objective of system sizing is to identify the minimum system which satisfies the load requirement. Or, to put it another way, the system size must be just large enough to meet the load requirement during the period of lowest insolation. For any location there will usually be a worst month of average daily insolation. It is important to select an array tilt angle that provides the maximum possible worst-month insolation. For consistency, the convention of assigning positive values to latitudes in the northern hemisphere (NH) and negative values to those in the southern hemisphere (SH) will be used. In general, if the worst month falls in the winter in the NH (or summer in the SH), the optimal array tilt angle is the latitude plus 23°. For a worst month falling in summer, in the NH (or winter in the SH), the optimal array tilt angle is approximately the latitude angle minus 23°. For the worst month falling in spring or autumn, the optimal array tilt angle is equal to the latitude. The worst-month average daily insolation at optimal array tilt, I_{WM}, is one of the three input values that we shall use for preliminary system sizing.

The array tilt angle that provides the maximum insolation during the worst month of the year will not do so several months later when the relative sun angle has greatly shifted. One change of original tilt angle during the year can increase the annual insolation collected by a few percent. (See Figs. H-1 to H-8, Appendix H.) Day-to-day adjustment in tilt angle can increase annual insolation collected by about 10 percent.

12.2 Overall System Efficiency

Overall system efficiency, η_{sys}, is the combined efficiency of the modules, battery (if any), and other system components as they affect the electrical output of the system:

$$\eta_{sys} = \eta_M\langle T\rangle \times \eta_B \times \eta_0$$

(1) $\eta_M\langle T\rangle$, module efficiency at operating temperature, was described in section 3.2.2. For a representative 1985 module, η_M would be 11.5% at 28°C and 10.5% at 45°C for single crystal, rectangular, close-packed solar cells and 8.5% at 28°C and 7.8% at 45°C for polycrystal, rectangular, close-packed solar cells.

(2) η_B, battery efficiency, is defined as

$$\eta_B = 1 + f_n\ (\eta_{rt} - 1)$$

where

f_n is the fraction of the load met by the battery,

f_n = day load from batt.+ night load/total daily load

η_{rt} is the round trip efficiency of the battery (i.e., the ratio of the energy delivered by the battery during discharge to the total energy required to restore the initial state of charge). For photovoltaic type batteries, η_{rt} would be in the range of 75% to 80%, depending on duty cycle.

An example from a PV medical system application can be used to illustrate the calculation of battery efficiency. For this application the day/night ratio of load was 1.68 kWH/2.52 kWH and the total daily load is 4.2 kWH (Ref. 9-1). Assuming that the demand on the battery is essentially due to the nighttime load, and that

η_{rt} = 0.8, then

$$f_n = 2.52/4.2 = 0.6 \text{ and}$$

$$\eta_B = 1 + 0.6(0.8 - 1) = 0.88$$

(3) η_0 accounts for other system losses not included in η_M or η_B such as electrical power losses in the wiring and buses, battery self-discharge, and module degradation. The combined wire and self-discharge losses in a well-designed system are approximately 2%. Module degradation losses were discussed in section 3.2.3. For present-day glass-covered modules, assuming no catastrophic failures, these losses should be negligible. Thus, for purposes of preliminary design, η_0 may be taken to equal 0.98.

12.3 System Sizing Procedures

12.3.1 PV System Without Battery

Two typical daytime load situations will be examined:

(1) The user has a specific monthly average daily load requirement, L. From energy balance considerations,

$$A = L \;/\; I_{WM} \times \eta_M\langle T\rangle \times \eta_0$$

where array area, A, is the sum of the area of all modules in the array, I_{WM} is the average daily insolation in the month of lowest average daily insolation, and the two efficiencies, η_M and η_0, are as defined above. The system size in terms of array area can be readily determined, since L is given by the user, I_{WM} can be found as per section 12.1.2, $\eta_M\langle T\rangle$ is available from a module manufacturer's data sheet, and η_0 can be estimated as above.

(2) The user wishes to generate a certain annual average

daily energy, E_A. From energy balance considerations,

$$A = E_A \;/\; I_A \times \eta_M \langle T \rangle \times \eta_0$$

where the annual average daily insolation, I_A, is the sum of the 12 monthly values, I_M, (for the months 1, 2, 3 ...12) divided by 12.

For any calculated system size, there should be enough energy generated during the period, i.e., monthly (case 1) or annually (case 2), to satisfy the daytime load requirement, <u>on the average</u>. However, there will be days when the insolation will fall below the average for the period. Obviously such occasions will occur more frequently during the poorest insolation months. The result will be complete or partial loss of load function during these low insolation intervals. The converse, i.e., intervals of greater than average insolation, will also occur. At these times the array will generate more than average amounts of energy. In most instances this energy surplus will have to be dissipated.

A user with an indispensable or a nighttime load will not wish to lose load function during periods of low or no sun. for such applications a storage device will be needed to supplement any short-term shortfall in energy generation. For example, in water pumping applications a water storage tank or pond may be used to insure an uninterrupted supply. However, in most applications for which uninterrupted load function is desired, energy storage in the form of a electric storage battery is used.

12.3.2 PV System With Battery

All methods for sizing a PV system with battery storage involve constuction of a model of the system that simulates operation: array output, battery charge/discharge cycling, and electric-

al load demand. The array output is applied against the load demand; excess array output is stored in the battery; excess load demand is met by drawing from the battery. The system's energy flow is then tracked and the energy balance determined for a given time period. The energy output of an array of specific size, with given module performance characteristics, is estimated from the insolation data for the site.

As mentioned in section 12.1.1, the single greatest influence on insolation is cloud cover, a stochastic (random) phenomenon. Each of the three general PV system-sizing procedures described below recognizes the stochastic nature of insolation; however, each treats the problem differently.

(1) Arbitrary Design Margin Method. Values of average daily insolation are used in a simulated energy flow procedure to calculate array and battery size for a given site, module performance, array tilt angle, etc. Then, the array size is arbitrarily increased by X percent and the battery size by Y percent to account for "no sun" days or a "bad sunshine" year , i.e., the randon nature of insolation. This approach is the sizing procedure used by most vendors of PV systems. NASA has used this method for its "Quickie Sizing Program" and its SHEMESH, IBM 370 computer program.

(2) Arbitrary Weather Variable Factor Method. This method is similar to (1) above. The difference is that an arbitrary weather cycle variable is introduced to modify the array output. NASA has used this procedure with a simulated 4-day weather cycle. Ref. 3-9 provides the details of the procedure an an example of the calculation for the Tangaye Village System design.

(3) Insolation Probability Function Method. The calculational method is similar to (1) with one crucial exception. The probability of occurence of monthly average daily insolation is determined using an empirically derived insolation probability function (Ref. 12-4). This probability function is used in the sizing simu-

lation model procedure to provide a s m size that is related explicitly to a quatitative probability of loss of energy of the PV system in any given month. Ref. 3-11 outlines a procedure, and gives instructions for programming TI-59 or HP-67 calculators, to calculate monthly loss of energy probability (LOEP) for a system of given array and battery size. Similarly, a NASA program, SEOSCAR, devised by NASA engineer O. Gonzalles, has been programmed for the IBM 370/3033 computer. This latter program will calculate monthly LOEP, given an array and battery size, or calculate the array and battery size, given a desired monthly LOEP.

12.4 Simplified Method for Preliminary System Sizing

Using the SEOSCAR program, the author has prepared a set of rapid system sizing aids, Figures 12.4-1, 12.4-2 and 12.4-3, for the loss of energy probability in the worst-month, $(LOEP)_{WM}$, of 0.1 percent, 1 percent and 10 percent, respectively. Each figure contains plots of I_D vs. C_L for 9 values of I_{WM}. I_D, the average daily insolation required to meet the load demand, is defined as follows:

$$I_D = \frac{L}{A \times \eta_{sys}} = \frac{L \times 1000 \times \eta_M T}{P_T \times \eta_{sys}} \qquad /1/$$

where

A is the total area of all modules in the array in m^2,

P_T is the total power of the array in W, at the operating temperature, T, and standard irradiation, and

L is the average daily load demand, during the month under consideration, in units of kWH/day

$$C_L = \frac{B \times \text{Allowable DOD}}{L} \qquad /2/$$

where

B is the installed battery capacity, and

Allowable DOD is as described in section 4.4

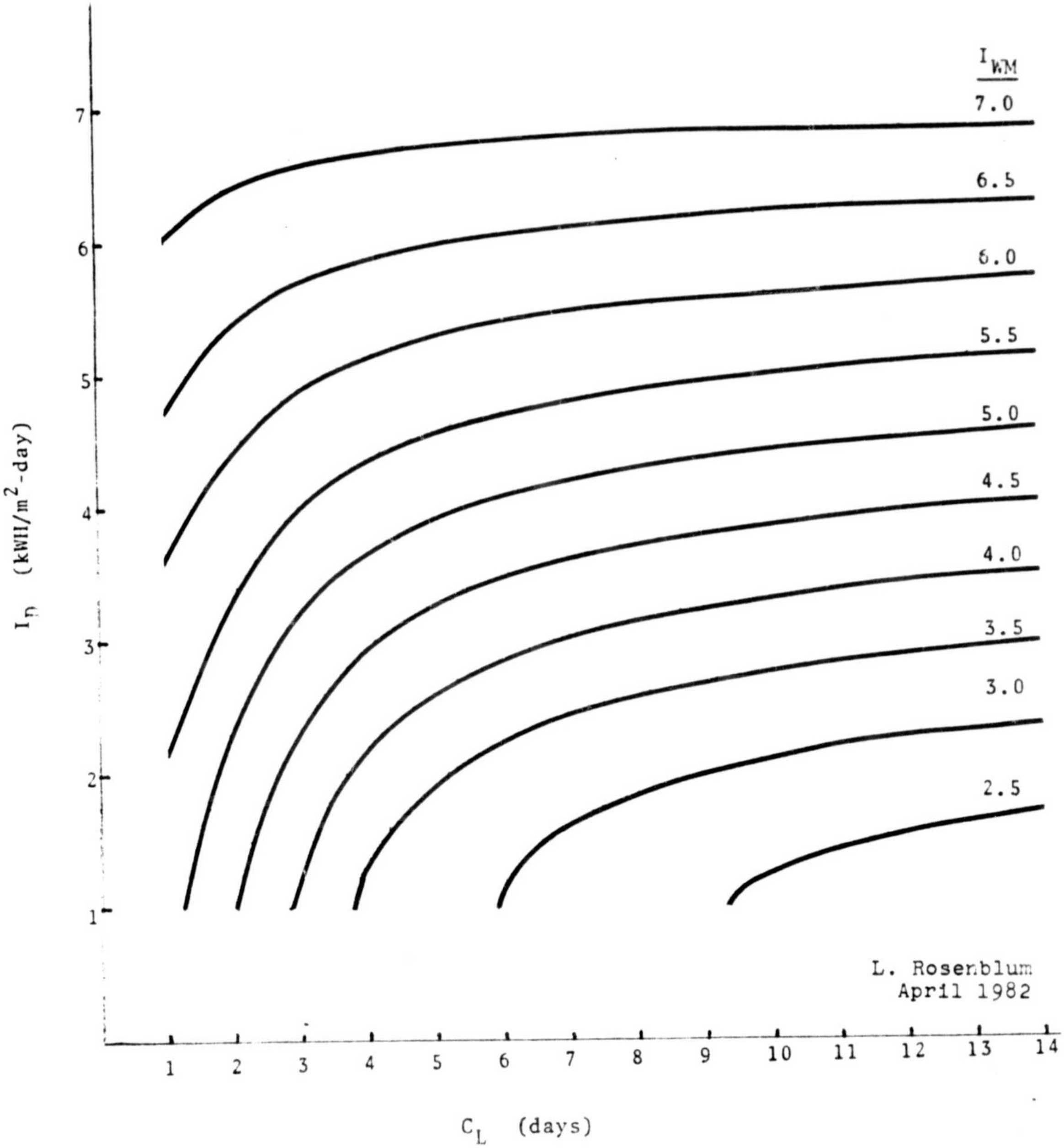


FIGURE 12.4-1 PV SYSTEM SIZING CURVES FOR $(LOEP)_{WM}$ = 0.1%

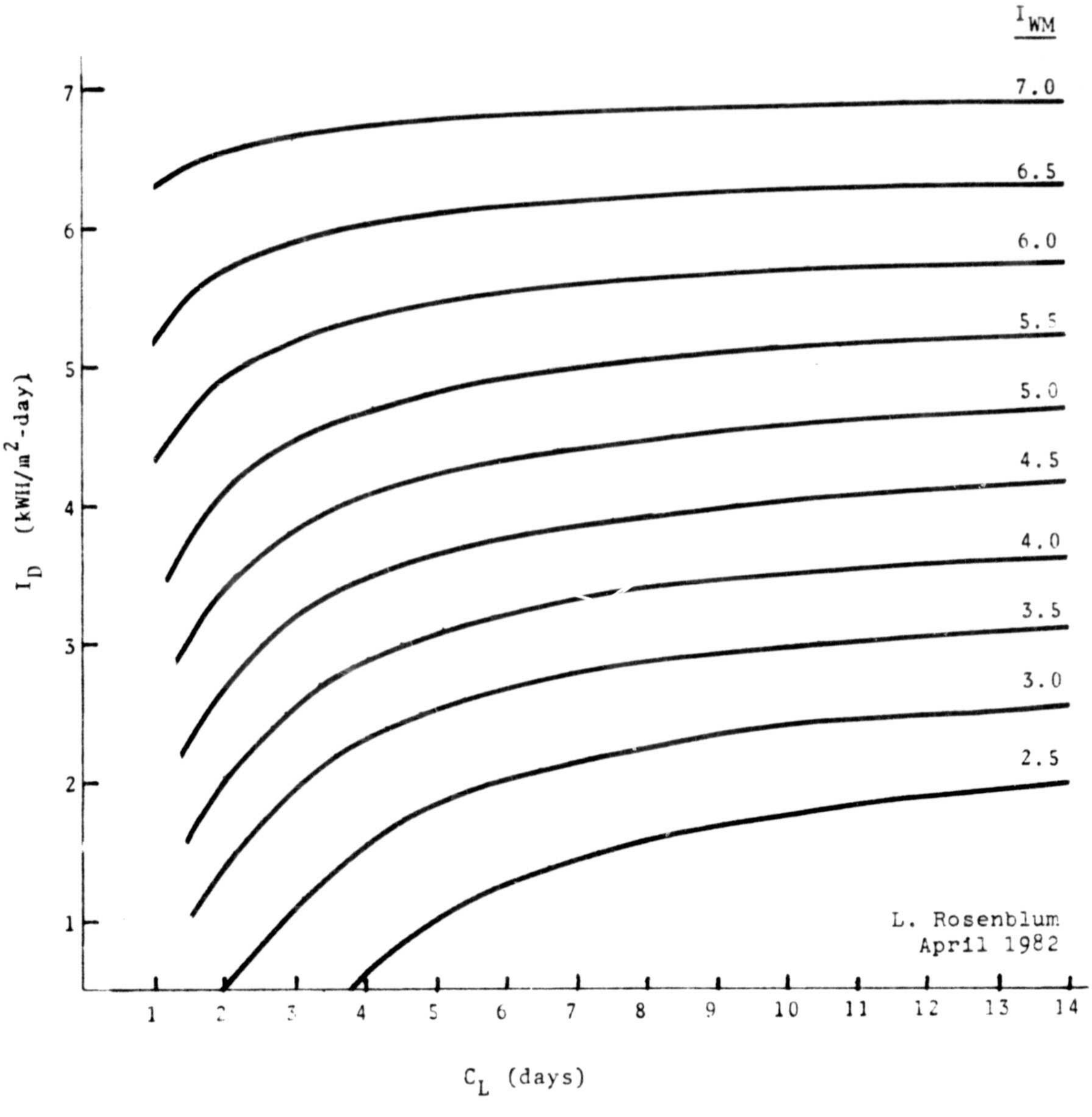


FIGURE 12.4-2 PV SYSTEM SIZING CURVES FOR $(LOEP)_{WM}$ = 1%

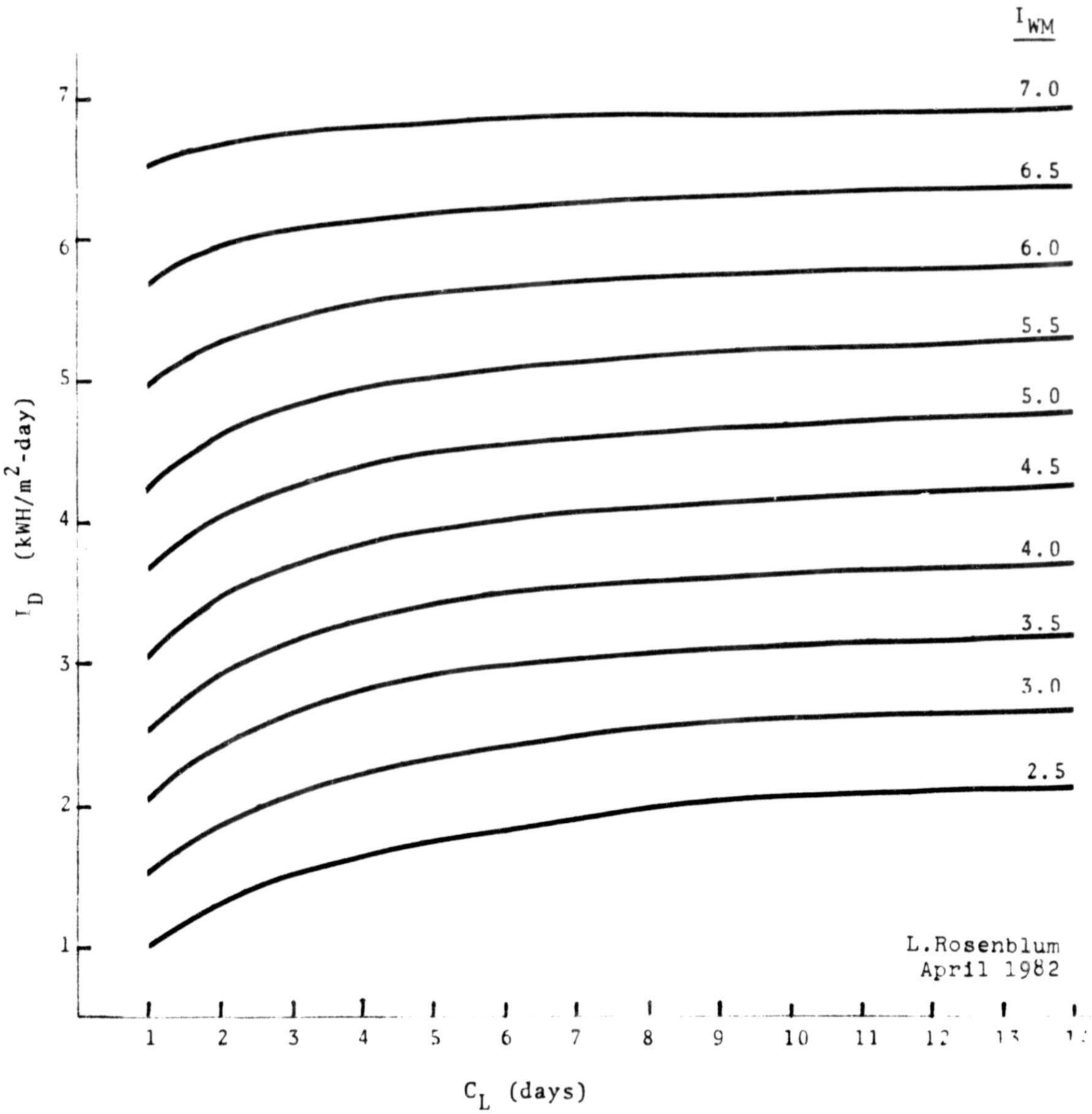


FIGURE 12.4-3 PV SYSTEM SIZING CURVES FOR $(LOEP)_{WM}$ = 10%

Each point on a selected I_{WM} curve yields a pair of values, an I_D (array size) value and a C_L (battery size) value, for a system which would exhibit the desired $(LOEP)_{WM}$. Obviously a large number of array and battery size combinations are possible for any given insolation condition and $(LOEP)_{WM}$. For reasons that will be discussed below, the region around the knee of the I_D vs. C_L curves is of the greatest practical interest for system sizing.

The use of the sizing curves can be best understood by working through several sample cases. For the examples that follow, the average daily load demand, L, is 4.2 kWH/day and is assumed to be constant throughout the year. (The variable load demand situation is discussed in section 12.6.) The fraction of the load demand met by the battery, f_n is 0.1. The pertinent conditions and efficiencies are as follows:

$\eta_o = 0.98$

$\eta_M = 0.082$ at 45°C

$\quad = 0.075$ at 60°C

Module power coefficient of temperature, $P_{TC} = -0.5$ percent/°C

$\eta_{rt} = 0.8$

Allowable battery DOD = 80 percent

$$\eta_{SYS} = \eta_M \eta_o [1 + f_n (\eta_{rt} - 1)]$$
$$= 0.082 \times 0.98 [1 + 0.1 (0.8 - 1)] = 0.079 \text{ at } 45°C$$
$$= 0.075 \times 0.98 [1 + 0.1 (0.8 - 1)] = 0.072 \text{ at } 60°C$$

Case 1: A system is desired that will have a service reliability of 10 percent $(LOEP)_{WM}$, for a site where I_{WM} = 4.9 kWH/m^2-day, and a 60°C operating temperature.

To determine an array and battery size which meet these conditions, we enter into Fig. 12.4-3 at about the knee of the curve for I_{WM} = 4.9 (interpolating between the 5.0 and 4.5 curves) and select a point given by I_D = 4.1 and C_L = 2.8. The selection of any other point on the curve in the same region would give somewhat different combinations of I_D and C_L and result in somewhat different combinations of array size and battery size; however, all combinations would satisfy the $(LOEP)_{WM}$ requirement. The array and battery sizes are as follows:

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$$I_D = \frac{L \times 1000 \times \eta_M \cdot T>}{P_T \times \eta_{SYS}}$$

$$4.1 = \frac{4.2 \times 1000 \times 0.075}{P_{60} \times 0.072}$$

P_{60} = 1070W
P_{28} = 1070 [1 + (0.005 x 32)] = 1240 W_p, array size

B = 2.8 x 4.2/0.8 = 15 kWH, installed battery capacity

Case 2: We wish to determine the array size for a system with the same operating temperature, I_{WM}, and installed battery size as Case 1 but for a 0.1 percent $(LOEP)_{WM}$.

Referring to Fig. 12.4-1, we see that for C_L = 2.8 and I_{WM} = 4.9, I_D is 2.9. The array size is as follows:

$$2.9 = \frac{4.2 \times 1000 \times 0.075}{P_{60} \times 0.072}$$

P_{60} = 1510W
P_{28} = 1510 x 1.16 = 1750 W_p, array size

For this particular example, the system with the higher reliability requires a 1750-1240/1240 = 41 percent larger array than the system with the lower reliability. The general implications of a system's service availability, as affected by choice of LOEP, were discussed in sections 11.2 and 11.4.3. The specific consequences relative to $(LOEP)_{WM}$ and $(LOEP)_A$ (the annual loss of energy probability) will be discussed in section 12.8.

Case 3: We wish to determine the $(LOEP)_{WM}$ for a system with an array, P_{28} = 1100 W_p, operating temperature 45°C, and battery, B = 14 kWH, for two sites: site A, I_{WM} = 5.5, site B, I_{WM} 5.7.

First we calculate I_D and C_L:

$$P_{45} = 1100/1.09 = 1010$$

$$I_D = \frac{4.2 \times 1000 \times 0.082}{1010 \times 0.079} = 4.3$$

$$C_L = 14 \times 0.8/4.2 = 2.7$$

Referring to Figures 12.4-1, 12.4-2, and 12.4-3, we find for I_D = 4.3, on the I_{WM} = 5.5 curve of each figure, the following values for C_L, respectively: 3.9, 2.5 and 1.1. The $(LOEP)_{WM}$ for the system, therefore, is approximately 1 percent. Using the same approach, we find that for I_{WM} = 5.7 the $(LOEP)_{WM}$ is approximately 0.1 percent.

12.5 Sizing for the Minimum-Cost System

As we move along any of the I_{WM} curves of Figures 12.4-1 to 12.4-3, the array and battery sizes are seen to vary oppositely. Therefore, we may anticipate that there will be one point on each I_{WM} curve--in the region of the knee of the curve--for which a single combination of array size and battery size will result in a minimum-cost system.

For a given I_{WM}, $(LOEP)_{WM}$, and η_{SYS}, the minimum-cost system can be found using Figures 12.4-1 to 12.4-3, together with a PV system cost equation having array area and installed battery capacity as the variable terms. Minimum-cost systems values were determined using the cost equation described in section 13.1. The results shown in Figure 12.5-1 where I_D and C_L values that yield the minimum-cost system are plotted vs. I_{WM} for 3 values of LOEP.

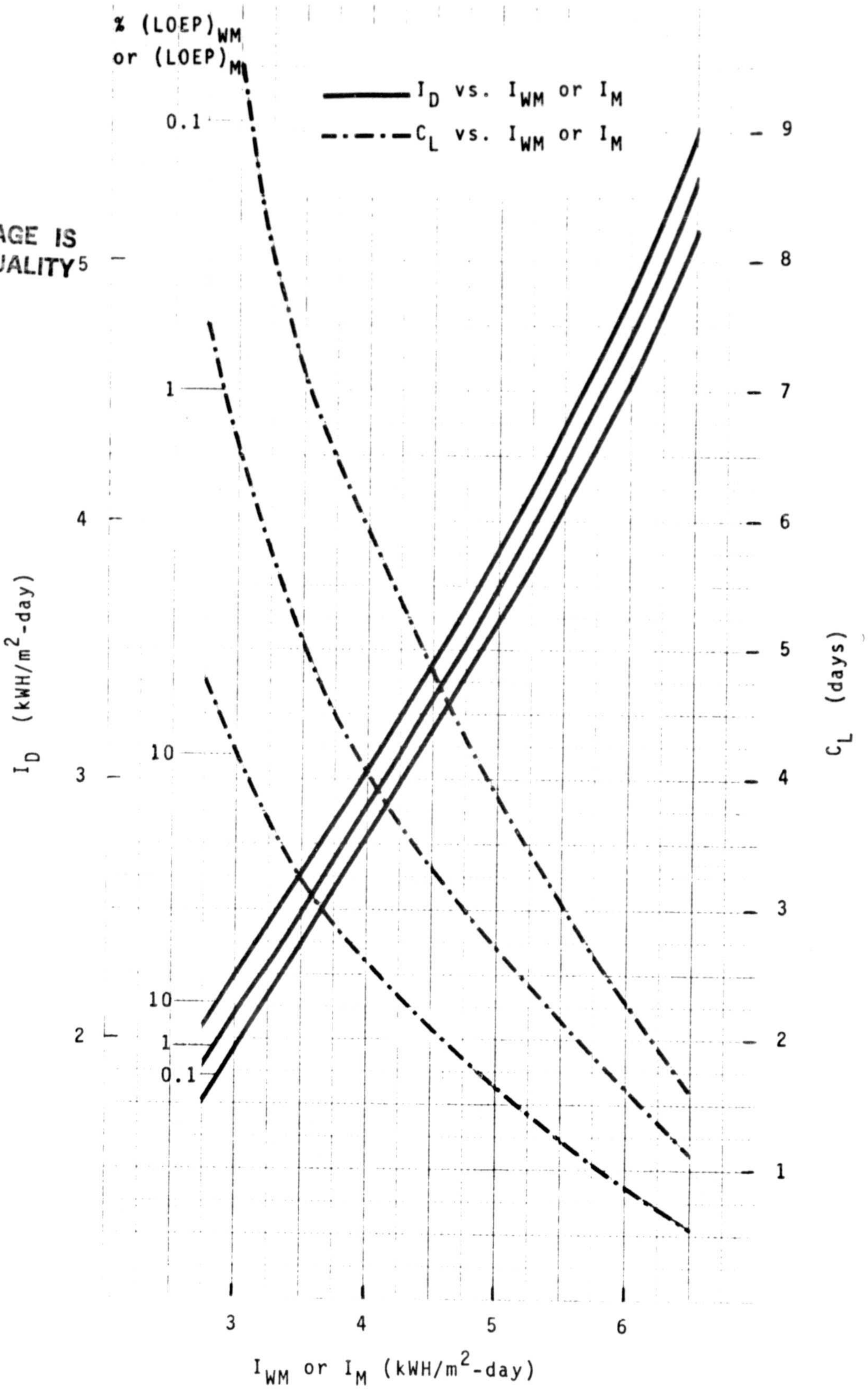

FIGURE 12.5-1 RAPID OPTIMUM SYSTEM SIZING AID (ROSSA)

The array dependent portion of the cost of present day systems is several times greater than the battery dependent portion. (N.B.: the array dependent costs include the modules, the array structure and foundation, the grounding system, and associated labor.) As a consequence, the value of η_{sys} can range from 0.10 to 0.08 without significantly changing the specific combinations of I_D and C_L values that yield minimum-cost systems. A range of η_{sys} of 0.10 to 0.08 would encompass all operating temperatures up to 60°C and all values of f_n from 0 to 1. In short, Figure 12.5-1 may be used to size systems for all operating conditions of practical interest. An illustration of the use of this rapid optimum system sizing aid (ROSSA) follows.

Case 4: Find the size of the minimum cost system for 10% and 0.1% $(LOEP)_{WM}$, for a site with I_{WM} = 5.0, L = 3.9, η_{sys} = 0.10 and η_M = 0.104 at 45°C, P_{TC} = -0.5%/°C, and the allowable DOD for the battery = 0.8.

From ROSSA we find for I_{WM} = 5 the following value for I_D and C_L, respectively:

0.1% $(LOEP)_{WM}$	3.6 and 3.85
10% $(LOEP)_{WM}$	3.9 and 1.60

With these I_D values, P_{28} can be calculated using equation /1/ and the relationship for the temperature conversion of power as follows:

$$P_{28} = \frac{L \times 1000 \times \eta_M\ 45}{I_D \times \eta_{sys}\ 45} \left[1 - \left(P_{TC}\left(45 - 28\right)\right)\right]$$

For 0.1% $(LOEP)_{WM}$,

$$P_{28} = \frac{3.90 \times 1000 \times 0.104}{3.60 \times 0.10} \left[1 - \left(-0.005\left(45 - 28\right)\right)\right] = 1230\ W_p$$

For 10% (LOEP), P_{28} = 1130 W_p.

B is calculated as follows:

$$B = \frac{L \times C_L}{\text{Allowable DOD}} = \frac{3.9 \times C_L}{0.8} = 4.88C_L$$

For 0.1% $(LOEP)_{WM}$, B = 18.8 kWH

For 10% $(LOEP)_{WM}$, B = 7.8 kWH

12.6 System Sizing for Variable Load Demand

In the four cases presented above, the average daily load demand was assumed to be constant throughout the year. However, there are applications for which the load demand varies from month to month. In this instance the system sizing procedure is similar to that previously described for constant load but necessitates 12 calculations -- one for each month of the year. An illustration of the procedure follows.

Case 5: Find the minimum cost system for an application located in the vicinity of Georgetown, Guyana for which the average daily load demand, L , varies by month as indicated in Fig. 12.6-1. The average daily insolation by month, I_M, is also listed in Fig. 12.6-1 (from Appendix H, Fig. H-3). The pertinent system and component conditions are the same as were used in Case 4. It is desired that the loss of energy probability, in any month of the year, $(LOEP)_M$, be no greater than 10 percent.

From ROSSA, Fig. 12.5-1, we find for each of the 12 values of I_M the corresponding value of I_D on the 10% $(LOEP)_M$ curve. For each I_D we calculate an array size, P_{28}:

$$P_{28} = \frac{L \times 1000 \times 0.104}{I_D \times 0.10} (1.09) = 1130\ L/I_D$$

Month	L	I_M	I_D	P_{28}
1	5	5.14	4.05	1400
2	5	5.29	4.15	1360
3	5	4.92	3.75	1510
4	4	5.20	4.10	1100
5	4	4.92	3.75	1210
6	4	4.88	3.75	1210
7	5	5.34	4.20	1350
8	5	5.52	4.35	1300
9	5	5.47	4.30	1310
10	6	5.51	4.35	1560
11	6	5.47	4.30	1580
12	5	5.00	3.90	1450

Figure 12.6-1 Case 5, Variable Load Demand: Input Data and Array Sizing Results

Inspection of the array size values, Fig. 12.6-1, indicates that the array size requirement has its greatest value, 1580 W_p, in the eleventh month. This array size will meet the load demand during any month of the year. Although the sixth month has the poorest insolation of the year, the load demand is such that the array size requirement for that month is only 1210 W_p.

To determine battery size, once we have established the array size, we return to Fig. 12.5-1. For I_M = 5.47, the insolation in the eleventh month, we find C_L = 1.3 for 10% $(LOEP)_M$. Therefore the required battery capacity is 1.3 x 6/0.8 = 9.8 kWH.

12.7 Comparison of System Sizing Procedures

For purposes of comparison we will examine the results of two different system sizing methods for a Rural Health Clinic PV system, installed in Gabon in 1984 under the U.S./Gabon Joint Program of Demonstration of Solar PV Power. The two methods are (1) an arbitrary design margin method used by the system contractor, Solavolt International, and (2) the insolation probability function method described in sections 12.4 and 12.5. The contractor's design margin technique consisted simply of applying a 20% "safety factor" to the estimated load. In other words he arbitrarily increased the estimated load by 20% prior to calculating system size.

The pertinent data and conditions follow:

Estimated average daily load requirement, L = 1.385 kWH/day; nighttime load is estimated to be 25% of the total.

Array: 640 W_p (16-40 W_p Solavolt MSP43E40 modules); fixed tilt angle of 10^o, facing north; estimated operating temp., 43^oC; $\eta_M\langle 28\rangle = 0.0917$; $P_{TC} = -0.00455$.

Battery: 24 kWH (24-Exide DH5 cells); allowable DOD = 0.20 (manufacturer's recommendation for battery life of 4 years minimum).

Insolation at -10^o tilt (month/I_M): 1/3.82; 2/4.45; 3/4.01; 4/4.72; 5/4.84; 6/4.28; 7/3.63; 8/4.16; 9/4.05; 10/3.94; 11/3.84; 12/3.80. (I_{WM} = 3.63 kWH/m^2-day)

First, it is of interest to calculate the service performance for the installed system, i.e., determine what a 20% "safety factor" system implies quantitatively in terms of loss-of-energy probability. To do this we begin by calculating I_D at operating temperature for the Solavolt system.

$$\eta_M\langle 43\rangle = 0.0917\left[1 - 0.00455(43 - 28)\right] = 0.085$$

$$P_{43} = 640\left[1 - 0.00455(43 - 28)\right] = 596 \text{ W}$$

$$\eta_B = 1 + 0.25(0.8 - 1) = 0.95$$

$$\eta_0 = 0.98 \text{ (assumed)}$$

$$\eta_{sys}\langle 43\rangle = 0.085 \times 0.95 \times 0.98 = 0.079$$

$$I_D = \frac{1.385 \times 1000 \times 0.085}{596 \times 0.079} = 2.50$$

Referring to the sizing curves, Figues 12.4-1, -2, and -3, for $I_D = 2.50$ and $I_{WM} = 3.6$, we find the following values for the battery parameter, C_L:

$\%(LOEP)_{WM}$	C_L	B, kWH
0.1	6.9	47.8
1.0	4.4	30.5
10	2.1	14.6

The battery size corresponding to each value of C_L can be found using equation /2/:

$$B = 1.385C_L/0.2 = 6.93C_L$$

The calculated values of B are listed in the above table.

A comparison of the installed battery size, 24 kWH, with the battery corresponding to each of the values of $(LOEP)_{WM}$, indicates that the Solavolt system has a $(LOEP)_{WM}$ between 1% and 10%.

Now, let us compare the installed Solavolt system to the "minimum-cost" system size calculated using ROSSA. For $I_{WM} = 3.6$ we find from Fig. 12.5-1 the following values for I_D and C_L at 3 values of $(LOEP)_{WM}$:

$\%(LOEP)_{WM}$	I_D	C_L
0.1	2.45	6.80
1.0	2.60	4.75
10	2.70	3.10

Array and battery size are calculated using equations /1/ and /2/:

$$P_{28} = \frac{1.385 \times 1000 \times 0.85}{0.079 I_D} \quad 1 - 0.00455\ (28 - 43) \quad = 1590/I_D$$

$$B = 6.93 C_L$$

The following table displays the results:

Sizing Method	$\%(LOEP)_{WM}$	P_{28}, W_p	B, kWH
ROSSA	0.1	650	47
"	1.0	610	33
"	10	590	22
Solavolt	----	640	24

Exact agreement between ROSSA and any particular contractor's calculated minimum cost system is not expected, because of two practical considerations that influence a contractor's design. First, modules are produced in discrete unit sizes of power and voltage. Thus, when a module selection is made, the contractor's

sizing program is constrained to move in discrete power steps (e.g., 40 W steps in the Solavolt case under discussion) in arriving at a system size which meets the load requirement. Obviously, an array size calculated by such a procedure, of necessity, will be equal to, or greater than, the size just needed to match the load requirement.

Second, component, material, overhead, and labor costs are manifestly not the same for each contractor. Thus, with the same load requirement, the array and battery sizes which produce a minimum cost system will vary from contractor to contractor.

In view of the above, the ROSSA array size usually will be somewhat smaller than that of an installed system, since the ROSSA sizing method permits a continuous variation of array power while the installed-system design procedure does not. Further, ROSSA system sizing numbers can be considered medial values within the range of present, contractor-designed, minimum-cost sytems, since the costs (section 13.1.1) used to derive Fig. 12.5-1 are based on cost information from systems installed by several different contractors.

12.8 Significance of Loss of Energy Probability Values

For purposes of system sizing and analysis, the two loss of energy probability terms of interest are $(LOEP)_{WM}$ and the annual loss of energy probability, $(LOEP)_A$. The latter is the numerical average of the twelve monthly values of loss of energy probability. It is observed that $(LOEP)_A$ falls in the range of 20 to 40 percent of the value of $(LOEP)_{WM}$. Figure 12.8-1 displays a typical distribution of the twelve monthly loss of energy probability values for 10 and 1 percent $(LOEP)_{WM}$.

A system designed to a $(LOEP)_{WM}$ of 10%, for example, should

ARRAY SIZE= 1400.000WP BATTERY SIZE= 7.891KWH

MONTH	IT	SDEV	LOAD	LOEP
1	5.14	2.37	4.200	4.0
2	5.29	2.30	4.200	1.9
3	4.92	2.04	4.200	3.1
4	5.20	2.13	4.200	1.4
5	4.92	2.32	4.200	7.8
6	4.88	2.35	4.200	10.0
7	5.34	2.26	4.200	1.3
8	5.52	2.21	4.200	0.5
9	5.47	2.02	4.200	0.2
10	5.51	2.25	4.200	0.7
11	5.47	2.40	4.200	1.4
12	4.97	2.42	4.200	8.3

LOEP MIN= 0.2% LOEP MAX=10.0% LOEP AVE= 3.4%

ARRAY SIZE= 1400.000WP BATTERY SIZE= 16.250KWH

MONTH	IT	SDEV	LOAD	LOEP
1	5.14	2.37	4.200	0.3
2	5.29	2.30	4.200	0.1
3	4.92	2.04	4.200	0.1
4	5.20	2.13	4.200	0.0
5	4.92	2.32	4.200	0.7
6	4.88	2.35	4.200	1.0
7	5.34	2.26	4.200	0.0
8	5.52	2.21	4.200	0.0
9	5.47	2.02	4.200	0.0
10	5.51	2.25	4.200	0.0
11	5.47	2.40	4.200	0.1
12	4.97	2.42	4.200	0.8

LOEP MIN= 0.0% LOEP MAX= 1.0% LOEP AVE= 0.3%

Load = 4.2kWH/day

η_{sys} = 0.072 @ 60°C

Insolation: Georgetown, Guyana, Figure H-3

Figure 12.7-1 Typical Distribution of Monthly Values of Loss of Energy Probability for 10 and 1% $(LOEP)_{WM}$

experience, on the average, 3 days during the worst month when the available energy (i.e., energy generated by the array plus the available battery capacity) is insufficient to meet the load demand. Likewise, a system with a 10% $(LOEP)_A$ should experience, on the average, about 36.5 days during the year when the energy available is insufficient to meet the load demand.

The annual loss of energy probability number for a specific system design can be used to estimate the service performance parameter, availability. Referring to section 11.2, we see that the annual availability for a PV system is

$$A_{PV} = (1 - (LOEP)_A)\ (1 - F_C)\ (1 - M)$$

We may reasonably assume that M = 0. Further we can assign a value of 0.03 to F_C, based on earlier PV experience (section 11.4.3). For a 10% $(LOEP)_{WM}$ system design, for example, $(LOEP)_A$ is estimated, as above, to be between 2 and 4 percent. Using the average, 3 percent, we find the annual availability of this system design to be

$$A_{PV} = (1 - 0.03)\ (1 - 0.03) = 0.94$$

In an average year, then, we might expect 365 (1 - 0.94) = 22 outage days. Outages for half of the days are associated with insolation deficiencies and would be expected to occur mainly in the poorer sun months. The remaining outage days are associated with component failures and may be expected to occur randomly through the year. Insolation related outages are partial in nature, resulting in a diminished energy generating capability. As such, with appropriate load shedding (automatic or manual) system operation can continue uninterrupted.

The reader should bear in mind that loss of energy probability values are derived from probability mathematics. Thus, they

do not represent certainties; rather, they denote probability of outcome. Nevertheless, loss of energy probability is an indispensible element for system design and comparative analysis. It allows the application of explicit design performance criteria; it provides an objective basis for the design and comparison of systems.

By contrast, it is the current general design practice to size PV systems by the use of the arbitrary design margin method, in other words, using "best engineering judgement" to determine what constitutes a "reliable" system. Thus, in the absence of explicit service performance design criteria, a contractor must maneuver between the Scylla of overdesign to insure product "reliability" and the Charybdes of underdesign to be competitive in price with others.

Finally, it is evident that comparison of systems is meaningless without a common frame of reference. Service performance, as embodied in the (LOEP) values, provides a common frame of reference. Employing these values, valid comparisons can be made of (1) competing independent designs, (2) system design options and associated costs, or (3) PV system vs. competitor systems. Such analyses are central to the interests and concerns of designers, manufacturers, vendors, and users.

SECTION 12
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13.0 System Cost

The objectives of this section are: (1) to determine the relation of PV system cost to the system design parameters I_{WM} and $(LOEP)_{WM}$; (2) to make projections of cost trends; and (3) to compare PV and diesel-generator levelized energy costs.

13.1 Capital cost

The capital cost of a PV system to the user (i.e., the selling price) embraces all costs for labor, materials and parts, as well as the manufacturer's overhead and profit. A PV system includes the following elements: solar cell modules, array structure and foundation, electrical grounding, site preparation and security, electrical connectors and conductors, controls, regulators, instrumentation, and, when used, storage battery and enclosure. All items of labor, materials and parts, other than solar cell modules, are referred to as the balance-of-system, BOS (Ref. 13-1).

13.1.1 PV Sytem With Battery

Costs for a PV system with battery fall into one of three categories, namely, cost directly related to the area of the array, C_a, in $\$K/m^2$; cost directly related to the capacity of the battery, C_b, in $K/ kWH; anu the fixed costs per unit load, C_o, in $K/kWH/day. Using these categorical costs, a linear equation can be set up to describe the system capital cost per unit load requirement, C, in $K/kWH/day, as follows:

$$C = C_o + aC_a + bC_b$$

where a is the ratio of array area to load, A/L, and b is the ratio of installed battery capacity to load, B/L.

The major cost categories represented by C_o, C_a, and C_b each include several several sub-categories. For example, C_a would include costs related to the modules and those related to labor and materials for support structure, wiring, electrical protection, and installation. The values of a and b are related directly to the system design parameters, I_{WM} and $(LOEP)_{WM}$.

Obviously, the validity and accuracy of any PV system cost estimate will hinge on the validity and accuracy of the BOS and module cost data used. The credibility of projected costs will depend on the credibility of the assumptions made. The cost estimates made here are based on a critical distillation of 8 years of cost data covering two dozen PV stand-alone systems procured by the NASA Lewis Research Center and others. The assumptions made are cataloged below. System cost,C, as used here represents a manufacturer's selling price, in thousands of dollars (1985$) per kilowatt-hour per day of load requirement, for an installed system, less shipping costs.

For a 1985 system the following conditions are assumed: η_{sys} = 0.10 at 45°C; module cost, 7 $/$W_p$; mark-up to account for overhead, warranty, profit, etc., 60% on labor, 25% on materials (Ref. 13-2); production volume, small. For a 1989 system the same conditions as for 1985 were assumed, with the following changes: η_{sys} = 0.12 at 45°C; module cost, 5 $/$W_p$; production volume, large (greater than 10,000 units/year), resulting in two doublings of 90% learning curve for labor costs and in 20% discount on materials and parts for large volume purchases. For a late 1990's system the same conditions as for 1989 were assumed, with the following changes: η_{sys} = 0.135 at 45°C; module cost, 2.5 $/$W_p$. All costs are in 1985 dollars.

The following table lists the cost factors C_o, C_a, and C_b, by year.

Year	C_o	C_a	C_b
1985	0.59	1.19	0.25
1989	0.47	0.98	0.24
Late 1990's	0.47	0.68	0.21

Plots of the selling price of optimum-size (i.e., minimum-cost) PV systems vs. I_{WM}, for three values of $(LOEP)_{WM}$ are displayed in Figure 13.1-1 for 1985, 1989, and the late 1990's. Selling price (including installation but not shipping) is expressed in thousands of dollars (1985$) per killowatt-hour per day of load requirement.

Over the range of insolation conditions that might be found in the developing world, the price of a 1985 system, per unit load requirement, increases approximately three times from the best insolation sites to the worst. In regions of moderate insolation, there is a price difference of about $1000 per unit load requirement, between a 0.1% and 10% $(LOEP)_{WM}$ system. The insolation at a specific site is not within control of the user or the designer; the choice of service performance is. In fact, as Fig. 13.1-1 indicates, there is a significant financial incentive to avoid over-design of the system. Based on the discussion in sections 11.4.3 and 12.8, we find that a 10% $(LOEP)_{WM}$ system should provide a service availability equal to, or better than, competitor systems in rural and remote regions. Therefore, unless otherwise indicated by special requirements, the 10% $(LOEP)_{WM}$ system should be the one of economic choice.

As stated, the 1985 prices assume a system efficiency of 10%. It is found that an increase or decrease of one percentage point in system efficiency results in a 9% decrease or increase, respectively, in the price of a 10% $(LOEP)_{WM}$ system. By way of illustration, if, in a 10% $(LOEP)_{WM}$ system, we should substitute for the original

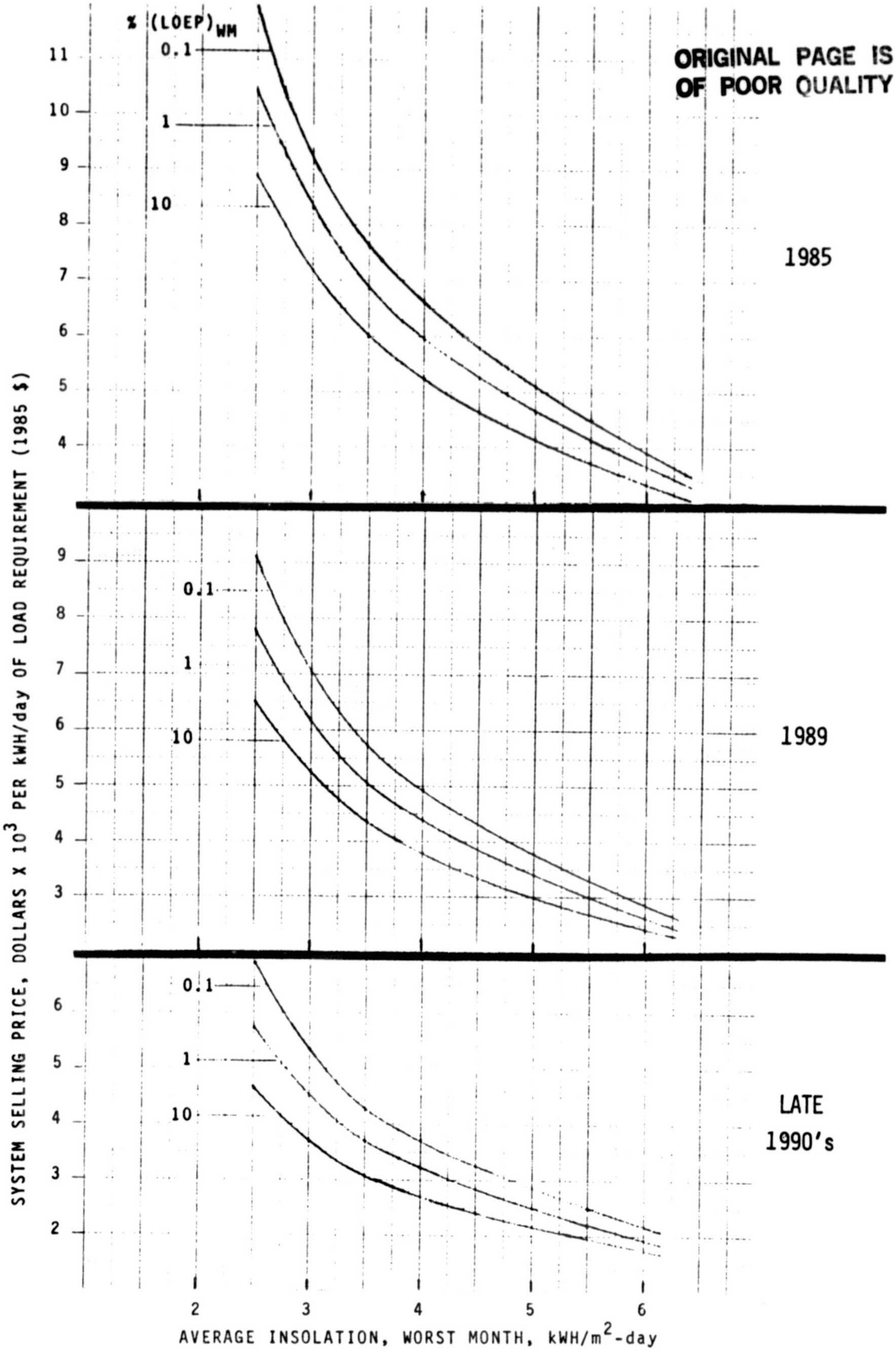

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FIGURE 13.1-1 PV SYSTEM PRICE AS A FUNCTION OF I_{WM} AND $(LOEP)_{WM}$

module one that is one percentage point lower in efficiency, the system price per unit load requirement would then be 9% greater. In this instance, the lower efficiency module requires additional array area to provide the same amount of energy generation as the more efficient module. The cost increase, then, is effectively due to costs associated with additional array support, structure, foundation, and labor.

13.1.2 PV System Without Battery

The capital cost per unit load requirement of a PV system without battery, C*, is given by the following equation:

$$C^* = C_o/2 + aC_a$$

For a simpler system without a battery, it is found that that C_o, the fixed cost (which is related mainly to the cost of instruments, controls and regulators) is about one half that of the more complex system with a battery.

An example of the calculation of the capital cost of a PV system for water pumping follows. The conditions are:

annual average daily water requirement, W, $20m^3$/day;
total pumped head, H, 30 m
pump-motor efficiency, 0.39;
$\eta_{sys} = \eta_M \times \eta_0 = 0.10$;
annual average daily insolation, I_A, 4.9 kWH/m^2-day.

The area parameter,

$$a = A/L = A/I_A\eta_{sys}A = 1/I_A\eta_{sys} = 1/(4.9 \times 0.10) = 2.0$$

C_o and C_a can be found in the table in section 13.1.1. Therefore,

$$C^* = 0.59 + 2.0(1.19) = 2.7 \text{ \$K/kWH/day}$$

The water-pump energy requirement, E_w, is given by

$$E_w = \frac{2.71 \times 10^{-3} \times H}{\text{Pump-Motor Effic.}} = \frac{2.71 \times 10^{-3} \times 30}{0.39} = 0.21 \text{ kWH/m}^3$$

and the annual average daily load requirement is

$$L_A = E_w \times W = 0.21 \times 20 = 4.2 \text{ kWH/day}$$

The capital cost of the PV system is $C^* \times L_A = 2.7 \times 4.2 = 11.3$ \$K.

13.2 Module and BOS Costs

Figure 13.2-1 presents a plot of module and BOS costs versus year for I_{WM} = 5 kWH/m^2-day and 10% $(LOEP)_{WM}$. The pertinent cost figures were extracted from the detailed cost estimate calculations used to derive system selling price (Fig. 13.1-1). BOS costs are subdivided into Battery and Other cost categories, to further elucidate the contribution of the major component costs. Incidentally, although Fig. 13.2-1 represents a single insolation condition, it is found that the module to BOS cost ratio and the cost trends remain effectively the same for other values of I_{WM}.

From Fig. 13.2-1, it is evident that module cost in absolute value has declined markedly since 1977. As a percentage of the total system price, for the stated conditions, module cost has dropped from 64% in 1977 to 50% in 1985, and is projected to drop to 32% in the late 1990's.

Battery cost in absolute value is predicted to remain fairly constant, in as much as (1) lead-acid batteries are the product of a mature technology and (2) manufacturing cost estimates made for new

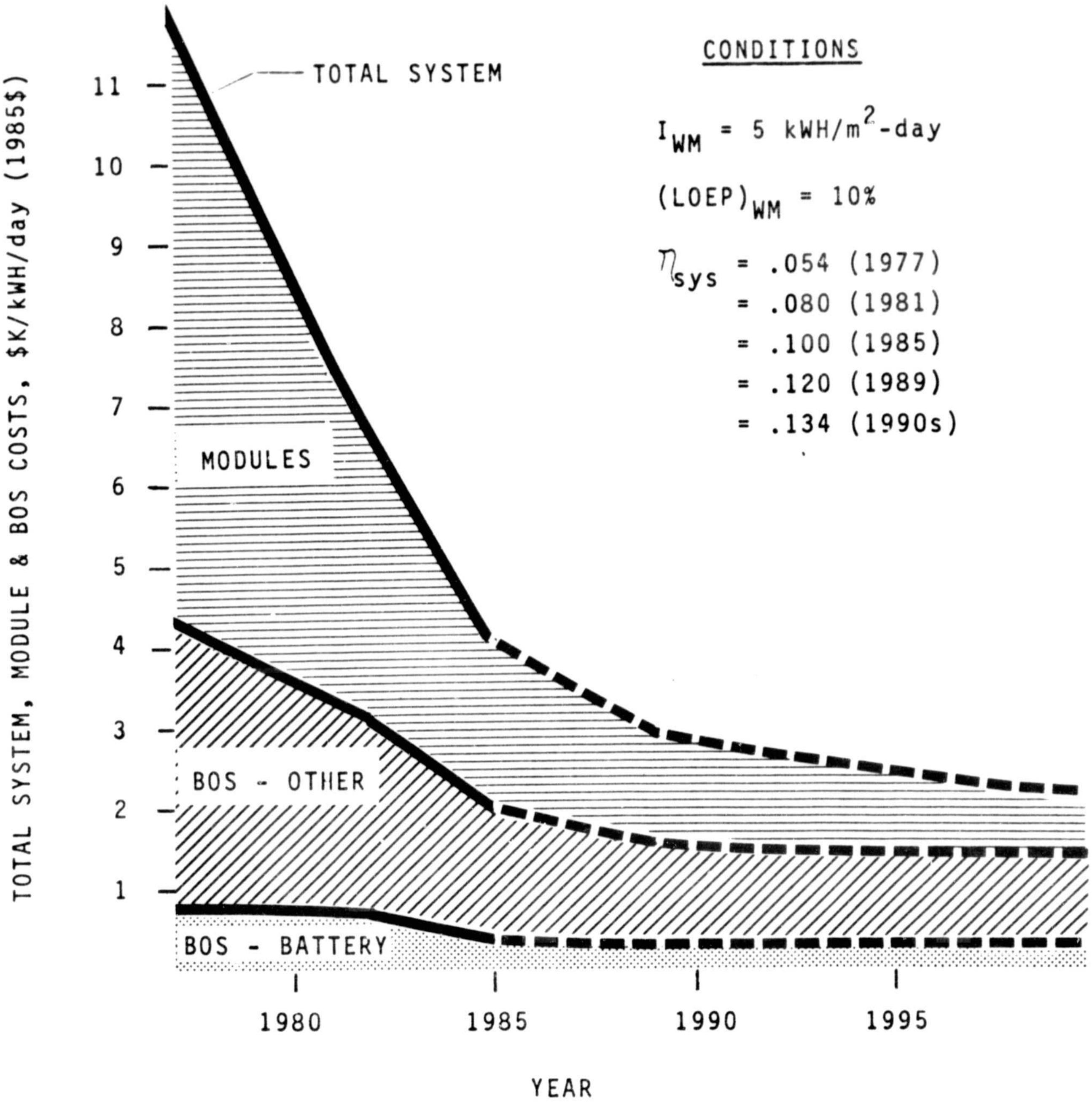


FIGURE 13.2-1 PV SYSTEM, MODULE AND BOS COST ESTIMATES

technology energy storage devices, such as REDOX, soberly promise only small cost reductions (Ref. 13-3). As a percentage of the total system cost, the battery is projected to increase from the present 9% to about 16% in the late 1990's.

The cost trends described above have important implications concerning the technical feasibility and the economic desirability of producing PV systems in developing countries. The manufacture of modules, which in the future may, if the projection is correct, constitute 32% of the total system price and which represents the most capital-intensive and technically difficult system component, appears to have little merit in this context. On the other hand, the in-country assembly of system components (purchased or locally produced) and the installation of systems, accounting for up to 68% of the total system price, should provide significant financial and economic advantages to developing countries.

13.3 Levelize Energy Costs

Levelized energy costs for PV and diesel-generator systems were calculated by the the standard procedure described in Ref. 13-4. An outline of the method follows. First, the present value of the system cash flows, P_{PV} and P_{DG}, for the PV and diesel-generator, respectively, are calculated. The present value of a cash flow is its real value adjusted for interest that could be earned, or must be paid, between the time of actual flow and the specified "present" time. The method of calculation of present value is given below.

(1) PV System Present Value

$$P_{PV} = C_{PV} + OM_{PV} + BR_{PV}$$

where C_{PV} is the PV system capital cost in dollars, OM_{PV} is the operation and maintenance present value, and BR_{PV} is the replacement battery present value.

$$OM_{PV} = OM_0 \frac{1}{k}\left[1 - (1 + k)^{-N}\right]$$

where OM_0 is the first year's operation and maintenance cost in dollars, k is the discount rate, and N is the system lifetime in years.

$$BR_{PV} = B_0 \sum (1 + k)^{-n_i}$$

where B_0 is the initial battery cost in dollars and n_i is the number of years to the i^{th} replacement.

(2) Diesel-Generator Present Value

$$P_{DG} = C_{DG} + OM_{DG} + DR_{DG} + F_{DG}$$

C_{DG} is the capital cost of the diesel-generator system in dollars. The operation and maintenance present value,

$$OM_{DG} = OM_0 \frac{1}{k}\left[1 - (1 + k)^{-N}\right]$$

where OM_0 is the first year's O & M cost in dollars. The replacement diesel present value,

$$DR_{DG} = D_0 \sum (1 + k)^{-n_i}$$

where D_0 is the initial cost of a diesel in dollars. The fuel cost present value,

$$F_{DG} = F_0\left(\frac{1 + g}{k - g}\right)\left[1 - \left(\frac{1 + g}{1 + k}\right)\right]^N$$

where F_0 is the first year's fuel cost in dollars and g is the fuel escalation rate.

Next, the annualized cost is calculated. The annualized cost is the product of the system present value and the capital recovery factor, CRF, where

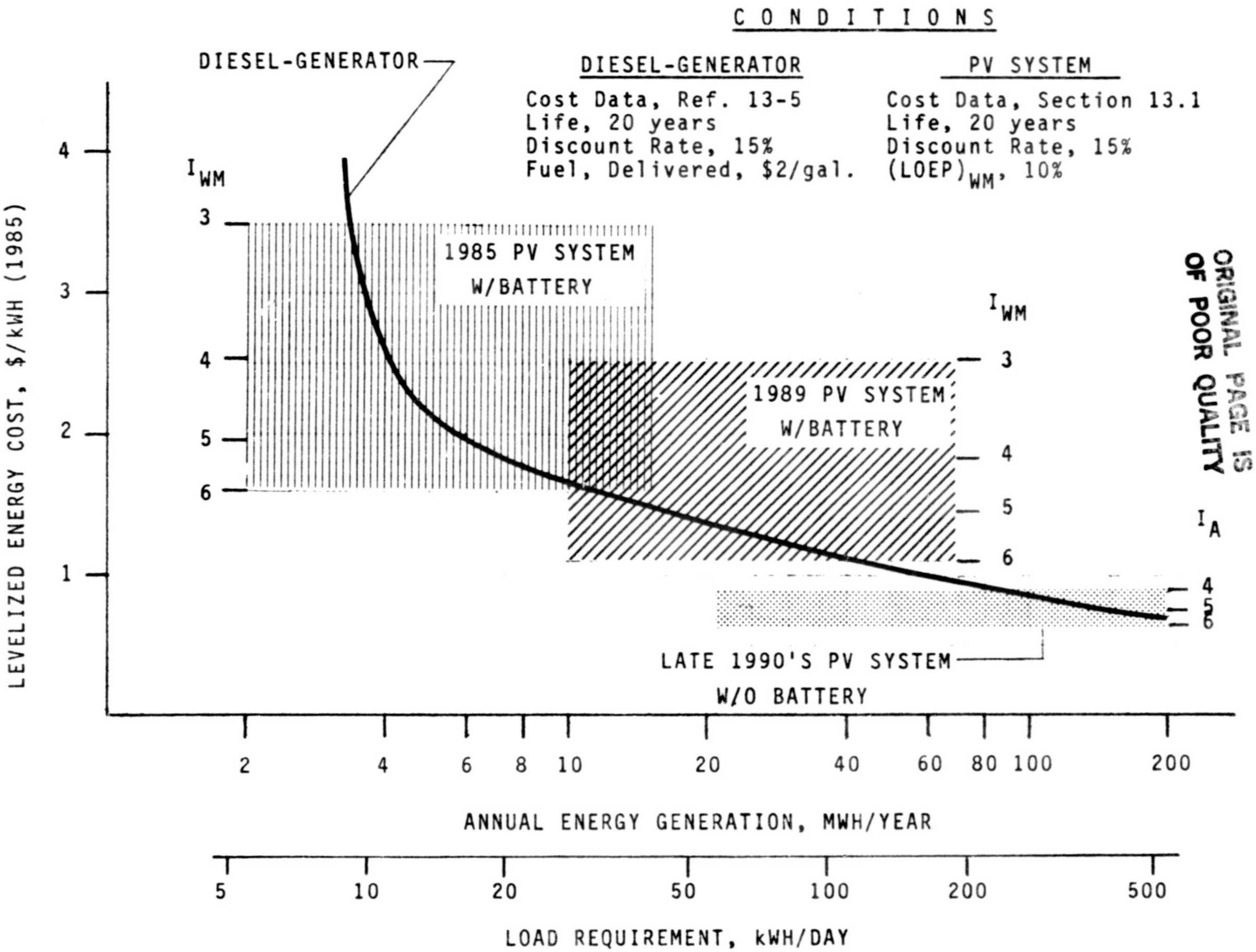
$$CRF = \frac{k}{1 - (1 + k)^{-N}}$$

Lastly, the levelized energy cost is simply the annualized cost divided by the annual energy generation of the system. Figure 13.3-1 displays a comparison of levelized energy cost, in dollars (1985$) per kilowatt-hour, for PV and diesel-generator systems as a function of annual energy generation or load requirement.

For PV systems, levelized energy cost is also a function of the available solar insolation. The cross-hatched areas of PV levelized energy cost encompass a range of average daily insolation (I_{WM} or I_A) of 3 to 6 kWH/m^2-day, covering the range of conditions that might be found at almost any site. PV systems with battery are assumed to be the most common type in use up through 1989. Therefore, to derive levelized energy costs for 1985 and 1989, the appropriate system capital costs were extracted from the information in Fig. 13.1-1 for a 10% $(LOEP)_{WM}$ system. Since the system sizing is keyed to the insolation in the worst month of the year, the annual energy generation will be 10 to 40% greater than that needed to satisfy the load requirement. This "excess" energy may be utilized for additional loads, if desired, but it is not counted in determining energy costs. By the late 1990's, it is assumed that the use of PV systems without battery will be widespread for bulk power generation. Therefore, in this period the system capital cost is calculated using the cost equation in section 13.1.2. The insolation parameter, I_A, is used to define the insolation range.

Other assumptions made are: 20 year system life; 15% discount rate; the annual O & M cost is 1% of the system capital cost; and 10 year battery life, where batteries are used.

FIGURE 13.3-1 PV SYSTEM VS. DIESEL-GENERATOR ENERGY COST COMPARISON



For diesel-generator systems, from 4 to 200 MWH/year generation, cost data is taken from actual operating experience of 10 power plants in Panama, Ref. 13-5. At the lower end of the annual energy generation scale, below 4 MWH/year, information from Ref. 13-6 was used to calculate levelized energy costs. The assumptions made are as follows: 20 year operating period; replacement of diesel engine after 15 years; 15% discount rate; zero fuel escalation rate; $2.00 per gallon delivered fuel cost (representative of the present unsubsidized cost).

As indicated in Fig. 13.3-1, the levelized energy cost of a PV system with battery in 1985, in regions of moderate to good insolation, is equal to, or less than, that of diesel-generator systems, for applications with load requirements of 25 kWH/day or less. Within this range of load requirement lie many applications of relevance to developing countries, such as water pumping for domestic and agricultural use, refrigeration, and lighting.

Over the next several years, it may be anticipated that PV system energy costs will drop to the point where PV systems will be cost-effective for powering loads of about 100 kWH/day -- suitable for small rural industry and village power applications. Finally, within 15 years, if the levelized energy cost projections are borne out, photovoltaics will become the least expensive, as well as the most reliable, source for decentralized bulk electric power generation in the developing world.

SECTION 13
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APPENDIX A

GLOSSARY

ALTERNATING CURRENT (AC) -- Electric current in which the direction of flow is reversed at frequent intervals, (50 to 60 cycles per second), as used in commercial grid power. Opposite of direct current (DC).

AMPERE, AMP -- A measure of electric current; the flow of electrons. One amp is 1 coulomb (6.3×10^{18} electrons) passing in one second. One amp is produced by an electric force of 1 volt acting across a resistance of 1 ohm.

ARRAY -- See photovoltaic array.

AVAILABILITY -- The fraction of time that a system (or subsystem) is neither forced out of service nor otherwise out of service because of scheduled or unscheduled maintenance.

BALANCE OF SYSTEM (BOS) -- Parts of a photovoltaic system other than the array; switches, controls, meters, power conditioning equipment, supporting structure for the array, and storage components, if any.

BORON -- A chemical element, atomic number 5, semi-metallic in nature, used as a dopant to make p-silicon.

CAPITAL COST -- The expenditure necessary to obtain a complete, operating power system.

CELL BARRIER -- A very thin region of static electric charge along the interface of the positive and negative layers in a photovoltaic cell. The barrier inhibits the movement of electrons from one layer to the other, so that higher energy electrons from one side diffuse preferentially through it in one direction, creating a current, and thus a voltage across the cell. Also called the depletion zone, or the cell junction.

CELL JUNCTION -- The area of immediate contact between two layers (positive and negative) of a photovoltaic cell. The junction lies at the center of the cell barrier or depletion zone.

CENTRAL STATION POWER -- The generation of electricity in large power plants with distribution through a network of transmission lines (grid) for sale to a number of users.

CONCENTRATOR -- A photovoltaic array which includes an optical component such as a lens or focusing mirror to direct incident sunlight onto a solar cell of smaller area.

CONVERSION EFFICIENCY (CELL) -- The ratio of the electric energy produced by a solar cell (under full sun conditions) to the energy from sunlight incident upon the cell.

DIFFUSE INSOLATION -- Sunlight received indirectly as a result of scattering due to clouds, fog, haze, dust, or other substances in the atmosphere.

DIRECT CURRENT (DC) -- Electric current in which electrons are flowing in one direction only. Opposite of alternating current (AC).

DIRECT INSOLATION -- Sunlight falling directly upon a collector. Opposite of diffuse insolation.

DISCOUNT RATE -- The interest rate used for computing present values, reflecting the fact that the value of a cash flow depends upon the time at which that flow occurs.

DISTRIBUTED POWER -- Generic term for any power supply located near the point where the power is used. Opposite of central power. See stand-alone, remote site.

DOPANT -- A chemical element added in small amounts to an otherwise pure crystal to modify its electrical properties. An n-dopant introduces more electrons than are required for the perfect structure of the crystal. A p-dopant creates electron vacancies in the crystal structure.

ESCALATION RATE -- The rate of change in the price of a commodity or service with time.

FILL FACTOR -- The ratio of the maximum power a photovoltaic cell can produce to the theoretical limit if both voltage and current were simultaneously at their maxima. A key characteristic in evaluating cell performance.

FLAT PLATE (MODULE OR ARRAY) -- An arrangement of solar cells in which the cells are exposed directly to normal incident sunlight. Opposite of concentrator.

GRID -- Network of transmission lines, substations, distribution lines, and transformers used in central power systems.

HOLE -- A vacancy where an electron would normally be in a perfect crystalline structure. A hole behaves as though it is a particle of unit positive charge.

IRRADIANCE -- The radiant power incident upon a unit area of surface.

IRRADIATION -- The radiant energy received by a unit area of surface during a given time period.

INSOLATION -- Solar irradiation.

INVERTER -- Device that converts DC to AC.

KILOWATT (kW) -- 1,000 Watts

KILOWATT HOUR (kWh) -- 1,000 Watt hours.

LEARNING CURVE -- A graphical representation of the relationship between cost or price per unit and the accumulated volume of units manufactured. It is used as a tool to predict cost and price trends.

LEVELIZED COST -- An equivalent uniform annual cost divided by the expected annual energy output, resulting in a cost per unit of energy, e.g., dollar per kilowatt-hour.

LIFE CYCLE COST -- An estimate of the cost of owning and operating a system for the period of its useful life; usually expressed in terms of present value of all lifetime costs.

LOAD -- Electric power being consumed at any given moment. Also, the device or appliance that utilizes electrical power.

LOSS OF ENERGY PROBABILITY (LOEP) -- The probability that an electrical generating system will be unable to provide the energy needed to meet load. It provides a measure of relative system reliability, e.g., a LOEP of 10 percent implies a probable loss of load 10 percent of the time during the period under consideration.

MEGAWATT (MW) -- One million Watts; 1,000 kilowatts.

N-SILICON -- Silicon containing a minute quantity of impurity, or dopant, such as phosphorus, which causes the crystalline structure to contain more electrons than required to exactly complete the crystal structure. There is no electrical imbalance, however.

OHM -- A measure of resistance to the flow of an electric current.

OPEN CIRCUIT VOLTAGE -- The voltage across a photovoltaic cell in sunlight when no current is flowing; the maximum possible voltage.

ORDER OF MAGNITUDE -- A factor of 10; used as a convenience in comparing large numbers.

PEAK LOAD, PEAK DEMAND -- The maximum load, or usage, of electrical power occurring in a given period of time, typically a day.

PEAK WATT OR WATT PEAK -- The amount of power a photovoltaic device will produce at noon on a clear day (irradiance at 1000 Watts per square meter) and a cell temperature of 28°C, when the cell is faced directly toward the sun.

PHOSPHORUS -- A chemical element, atomic number 15, used as a dopant in making n-silicon.

PHOTON -- A particle of light, which acts as an indivisible unit of energy; a quantum or corpuscle of radiant energy moving with the speed of light.

PHOTOVOLTAIC ARRAY -- An interconnected system of photovoltaic modules that functions as a single electricity-producing unit. The modules are assembled as a discrete structure, with common support or mounting.

PHOTOVOLTAIC CELL -- A device that converts light directly into electricity. A solar photovoltaic cell, or solar cell, is designed for use in sunlight. All photovoltaic cells produce direct current (DC).

PHOTOVOLTAIC COLLECTOR -- A photovoltaic module or array which receives sunlight and converts it into electricity.

PHOTOVOLTAIC MODULE -- A number of photovoltaic cells electrically interconnected and mounted together, usually in a common sealed unit or panel of convenient size for shipping, handling, and assembling into arrays.

PHOTOVOLTAIC SYSTEM -- A complete set of components for converting sunlight into electricity by the photovoltaic process, including array and balance-of-system components.

POLYCRYSTALLINE SILICON; POLYSILICON -- Silicon which has solidified at such a rate that many small crystals (crystalline) were formed. The atoms within a single crystal are symmetrically arrayed, whereas in crystallites they are jumbled together.

PRESENT VALUE OF CASH FLOW -- The real value of the cash flow adjusted for interest that could be earned between time of the actual flow and the specified "present" time.

P-SILICON -- Silicon containing a minute quantity of impurity, or dopant, such as boron, which provides insufficient electrons to exactly complete the crystal structure. There is no electrical imbalance, however.

RELIABILITY -- The probability that an item will perform its intended function for the intended period of time under stated conditions.

REMOTE SITE -- Not connected to a utility grid. See stand-alone; distributed power.

SEMICONDUCTOR -- Any material which has limited capacity for conducting an electric current. Certain semiconductors, such as a silicon, gallium arsenide, and cadmium sulfide, are uniquely suited to the photovoltaic conversion process.

SHORT CIRCUIT CURRENT -- The current flowing freely from a photovoltaic cell through an external circuit which has no load or resistance; the maximum current possible.

SILICON -- A chemical element, atomic number 14; semimetallic in nature; dark gray; an excellent semiconductor material. A common constituent of sand and quartz (as the oxide). Crystallizes in face-centered cubic lattice like diamond. See polycrystalline silicon.

SOLAR CELL -- A photovoltaic cell designed specifically for use in converting sunlight into electricity.

STAND-ALONE -- An isolated photovoltaic system not connected to a grid; may or may not have storage, but most stand-alone applications require battery or other form of storage. See remote site.

VOLT, VOLTAGE -- A measure of the force of "push" given the electrons in an electric circuit; a measure of electric potential. One volt produces one amp of current when acting against a resistance of one ohm.

WAFER -- A thin sheet of semiconductor material made by mechanically sawing it from a single crystal ingot.

WATT, WATTAGE -- A measure of electric power, or amount of work done in a unit of time. One amp of current flowing at a potential of one volt produces one watt of power.

WATT HOUR (WH) -- A quantity of electrical energy. One watt hour is consumed when one watt of power is used for a period of one hour.

WATT PEAK -- Same as peak watt.

APPENDIX B

TERRESTRIAL PV MEASUREMENT PROCEDURES

CONTENTS

Page

1.0 DEFINITIONS 1

2.0 NATURAL SUNLIGHT MEASUREMENT PROCEDURES 3
- 2.1 Measurement Equipment 3
- 2.2 Measurement Procedures 4

3.0 INDOOR MEASUREMENT PROCEDURES 5
- 3.1 Measurement Equipment 5
- 3.2 Measurement Procedures 6

4.0 CONCENTRATOR SYSTEM MEASUREMENTS PROCEDURES . . . 6

5.0 CALIBRATION OF REFERENCE CELLS 7
- 5.1 Measurement Equipment 7
- 5.2 Calibration Procedures 8

6.0 SOLAR SIMULATION AND COMMON TEST EQUIPMENT 9
- 6.1 Solar Simulator for Photovoltaic Measurements 9
- 6.2 Common Test Equipment 10

7.0 TERRESTRIAL SOLAR SPECTRUM 11

REFERENCES 11

TERRESTRIAL PHOTOVOLTAIC MEASUREMENT PROCEDURES

Many organizations and individuals are manufacturing and performing research on solar cells and arrays for terrestrial applications in support of both the Energy Research and Development Administration's National Photovoltaic Program and other various organizations. With so many organizations and individuals either manufacturing or doing research on solar cells for terrestrial applications, there is a need for a set of standard test procedures. These procedures would afford a common basis for comparing solar cells and also provide data for the design of large arrays. An interim manual was issued in July 1975 (ref. 1) by ERDA and the National Aeronautics and Space Administration (NASA) as a result of the ERDA/NASA Workshop on Terrestrial Photovoltaic Measurements held on March 19-21, 1975, in Cleveland, Ohio. A second workshop was held on November 10-12, 1976, at Baton Rouge, Louisiana. This manual incorporates approved revisions resulting from the ERDA/NASA 1976 Workshop.

This manual includes procedures for obtaining cell and array current-voltage measurements both outdoors in natural sunlight and indoors in simulated sunlight, a description of the necessary apparatus and equipment, the calibration and use of reference solar cells, some comments relating to concentration cell measurements, and a revised terrestrial solar spectrum for use in theoretical calculations.

1.0 DEFINITIONS

The following terms are used throughout the procedures:

(1) Reference solar cell - a cell made from the same material as the test cell/array and used to set simulator irradiance levels (The reference cell is provided by the central testing laboratory or is directly traceable to it. It is calibrated in units of short-circuit current output per unit of radiant energy input $(A/(W/m^2).)$

(2) Standard test conditions (STC) - cell temperature, $28^0 \pm 2^0$ C; irradiance, 1000 W/m^2 as measured with reference cell

(3) Short-circuit current (I_{sc}) - the current through a precision load resistor such that the voltage across the cell/array is less than 20 mV per junction

(4) Open-circuit voltage (V_{oc}) - the voltage across the unloaded (open) cell/array measured with a voltmeter having an internal resistance of at least 20 kΩ/V

(5) Maximum power - the power at the point on the current-voltage curve where the current-voltage product is a maximum

(6) Rated power - the power at a specified voltage

(7) Test cell area - the entire front surface area of the cell, including area covered by grids and contacts (For concentrator cells, test cell area is the area designed to be illuminated.)

(8) Module - smallest independent unit consisting of two or more interconnected cells

(9) Subarray - a specified size grouping of modules

(10) Array - a grouping of subarrays required for the particular application (Throughout the remainder of this manual, the term array will mean module, subarray, or array.)

(11) Array area - the entire frontal area including borders and frame

(12) Fill factor (FF) - the ratio of maximum power output of the cell/array to the product of open-circuit voltage and short-circuit current:

$$FF = \frac{\text{Maximum power}}{V_{oc} I_{sc}}$$

(13) Efficiency - the ratio of the maximum power output to the product of area and incident irradiance:

$$\text{Eff (\%)} = \left(\frac{\text{Maximum power}}{\text{Area} \times \text{Irradiance}}\right) \times 100$$

As an aid in understanding the measurement procedures in this document, figure 1 shows a block diagram of the different types of measurement methods.

The details of these methods are presented in subsequent sections of this document.

2.0 NATURAL SUNLIGHT MEASUREMENT PROCEDURES

The only accepted testing method for outdoor measurement of solar cells or arrays is the reference cell method. The reference standard to be employed for determining intensity in this method is a calibrated photovoltaic cell obtained from the recognized calibration facility (NASA Lewis Research Center, Cleveland, Ohio) or traceable to that facility. The reference cell must be supplied with a certificate of calibration indicating sensitivity. The calibration conditions for this cell are described in section 5. The reference cell must be made from the same type of material and have essentially the same spectral response characteristic as the cells or array of cells being tested.

2.1 Measurement Equipment

The following measurement equipment is used in the natural sunlight procedure.

(1) Reference cell: The intensity of natural sunlight is determined by the reference cell described previously and in section 5.

(2) Reference cell readout: The output of the reference solar cell is measured with equipment which meets the requirements described in section 6. 2.

(3) Temperature monitoring and control: The monitoring and control of reference cell temperature must be in accordance with the specifications given in section 6. 2. The temperature of all cells or arrays being tested must be measured to the same accuracy. For large arrays, cell temperatures should be monitored at a number of locations, with not less than 2 sensors per square meter of surface area.

(4) Alinement: The surfaces of the reference cell and the cell or array being tested must be maintained perpendicular to the direct solar beam throughout the test.

(5) Test cell fixture: The solar cell to be tested is mounted on a test

fixture which meets the requirements set forth in section 6.2. If an array of cells is being tested, array mounting and temperature control are at the option of the investigator. However, the actual temperature of the array must be reported, and four wire measurement techniques shall be employed insofar as possible.

(6) Test cell and array performance measurement equipment: The performance of the test cell or array is measured by using equipment which meets the requirements set forth in section 6.2.

2.2 Measurement Procedures

The reference cell and the cell (or array) to be tested are alined perpendicular to the Sun. The reference cell is coplanar with the test cell(s). The test location must be such that the entire cell or array and the reference cell are fully and uniformly illuminated. The surrounding area must be free of any highly reflective surfaces which would be capable of significantly increasing the solar and celestial radiation onto the cell or array. For work at low solar elevations (high zenith angles) the foreground should be dark (e.g., dark earth or blacktop). Highly reflective materials, even such natural materials as bright sand, must not be on the surface in the foreground.

The current-voltage (I-V) characteristic of the cell (or array) being tested is recorded at the same time as the output of the reference cell. The solar intensity as measured by the output of the reference cell must remain constant within 0.5 percent during measurement and must be at least 800 W/m^2.

Normally, during outdoor measurements the solar irradiance is not exactly 1000 W/m^2 and, unless controlled, the array cell temperature is not $28^{\circ} \pm 2^{\circ}$ C. If translation of the measured I-V curve to standard test conditions (STC - 1000 W/m^2 and 28° C) is desired, the following equations may be used (ref. 2):

$$\Delta I = I_{sc_1}\left(\frac{J_2}{J_1} - 1\right) + \alpha(T_2 - T_1)A$$

$$I_2 = I_1 + \Delta I$$

$$V_2 = V_1 + \beta(T_2 - T_1) - \Delta I R_s - K(T_2 - T_1)I_2$$

where I_2, V_2, J_2, and T_2 are current, voltage, irradiance, and temperature at STC; I_1, V_1, J_1, and T_1 are the measured values; α and β are the current and voltage temperature coefficients (β is negative); R_s is series resistance; K is a curve correction factor; and A is area. The R_s and K values must be obtained from experimental determination.

On warm days, where the uncontrolled cell or array temperature may get very high, it may be advantageous to shadow the test cell or array. Prior to measurement, the shadow is removed and data are taken quickly while the cell or array is close to ambient temperature.

3.0 INDOOR MEASUREMENT PROCEDURES

There are two test methods for the indoor measurement of cells and array. The first uses a steady-state solar simulator while the second uses a pulsed light (milliseconds) solar simulator. Both methods require a reference solar cell for intensity adjustment or measurement.

3.1 Measurement Equipment

The following test equipment is used in the indoor measurement procedures:

(1) Reference solar cell: The light intensity is adjusted or measured by using a reference cell which meets the specification described in section 5.

(2) Light source: The light source for the solar simulator is either a short-arc or long-arc xenon lamp or a dichroic filtered tungsten lamp. The simulator must meet the specifications of 6.1.

(3) Reference solar cell readout: The output of the reference solar cell is measured by using equipment which meets the requirement described in section 6.2.

(4) Temperature monitoring and control (steady-state): The temperatures

of the test cell and the reference cell are monitored and controlled as described in section 6.2. The test cell temperature must be maintained at $28^{o} \pm 2^{o}$ C.

(5) Test cell fixture (steady-state): The solar cell to be tested is mounted on a fixture which meets the requirements set forth in section 6.2. This test cell fixture may also be interchangeable with the reference cell.

(6) Test cell or array measurement equipment: The performance of the test cell or array is measured by using equipment which meets the requirements set forth in section 6.2.

3.2 Measurement Procedures

Steady-state method. - The light source is turned on and stabilized. The light source intensity is adjusted to 1000 W/m^2 as determined by measuring the short-circuit current of a calibrated reference solar cell held at a temperature of $28^{o} \pm 2^{o}$ C. The reference cell is replaced with a test fixture that is temperature controlled. The cell temperature is set to $28^{o} \pm 2^{o}$ C by using a dummy solar cell with a thermocouple attached to the top of the cell. The cell to be measured is placed in the test fixture, and the output is measured with four terminal contacts and appropriate readout equipment.

Pulsed method. - The procedures supplied by the pulsed simulator manufacturer are to be followed. The temperature of the test cell or array is measured and entered into the pulsed simulator data system. If a large number of cells or arrays are to be measured, and they are all at room temperature, then only an occasional temperature measurement is necessary. The reference cell and test cell or array are mounted coplanar and perpendicular to the pulsed beam. Care must be taken to ensure that the reference cell is included in a portion of the pulsed beam that meets the nonuniformity specification of section 6.1.

4.0 CONCENTRATOR SYSTEM MEASUREMENTS PROCEDURES

The measurement and characterization procedures to be used for solar cells intended for concentrator systems are to follow the procedures for

conventional cells in sections 2 and 3 with the added consideration that the intensity of solar irradiance is to be treated as a variable. The following additional points are to be considered:

(1) The cell performance and system performance are to be measured separately.

(2) The efficiency of a concentrator cell must use the cell area designed to be illuminated by the concentrator.

(3) The temperature of the cell junction must be maintained at $28^{o} \pm 2^{o}$ C.

(4) The nonuniformity of irradiance in the test plane must be less than ±20 percent. (This tolerance value is temporary until the effect of nonuniform irradiance on a concentrator cell is more fully understood.)

(5) The angle of incidence of concentrated irradiance on the cell must be within a full angle of 60^{o} (cone half-angle of 30 percent).

5.0 CALIBRATION OF REFERENCE CELLS

In order to make accurate performance measurements on solar cells under a variety of light sources, it is necessary that calibrated reference solar cells be available to set or measure intensity. This section describes the procedure to be used for calibrating these solar cell references under natural sunlight. (This calibration of reference cells is performed by NASA Lewis Research Center only and is included in this manual for information purposes.)

5.1 Measurement Equipment

The following measurement equipment is needed in the calibration of solar cells:

(1) Cell holder: The cell to be calibrated is mounted in a hermetically sealed container. The holder must be capable of being cooled or heated and a thermocouple or thermistor provided for temperature monitoring. Four output terminals (voltage + and -; current + and -) shall be provided.

(2) Irradiance monitor: Sunlight irradiance is measured by using a normal-incidence pyrheliometer (NIP). The reference cell being tested must

have the same field of view as the NIP (5° 42' full angle). The Sun must be tracked within $\pm 0.5^{\circ}$ during testing. The NIP is calibrated under the absolute cavity radiometric scale (PACRAD III).

(3) Test cell measurement equipment: The readout equipment specifications are given in section 6.2.

5.2 Calibration Procedures

The calibration of solar cells is performed in natural sunlight under the following conditions:

(1) Intensity: The direct beam sunlight irradiance must be between 750 and 900 W/m^2 at the time of the test, as measured by the NIP.

(2) Intensity stability: The atmospheric conditions must be sufficiently stable so that the variation in cell current is less than ± 0.5 percent during any 30-second measurement period.

(3) Clouds and haze: The sky must be clear and blue with no observable cloud formations within a 15° half-angle cone surrounding the Sun.

(4) Turbidity: The product of optical air mass and atmospheric turbidity during measurement must be less than 0.25 (turbidity determined from measurements at 500 nm). As an alternate, the ratio of uncollimated to collimated short-circuit current (using the NIP collimation angle) must be less than 1.2.

(5) Air mass: The optical air mass between the test cell and the Sun must be between 1 and 2. Cell temperature must be maintained at $28^{\circ} \pm 2^{\circ}$ C during measurement. Adequate measurement of cell spectral response is necessary to characterize cell type insofar as possible. Calibration values are reported as $A/(W/m^2)$ and are adjusted to the following atmospheric conditions:

Precipitable water vapor, cm	2
Turbidity (β)	0.12
Air mass	1.5
Ozone, cm	0.34

Calibration values must be the result of at least three measurements on

two different days. Short-circuit current measurements must be made with a 0.1-percent precision resistor at a voltage less than 20 mV across the cell.

It should be noted that the previous calibration procedure is based only on the normal incidence pyrheliometer. Another method uses a wide-angle detector (global method). But due to lack of correlation data, the NIP method is the only one currently used.

6.0 SOLAR SIMULATION AND COMMON TEST EQUIPMENT

6.1 Solar Simulator for Photovoltaic Measurements

There are three acceptable light sources for solar simulators used in terrestrial photovoltaic measurements: a short-arc steady-state xenon lamp, a long-arc pulsed xenon lamp, or a dichroic filtered tungsten lamp (ELH type). The source is modified by optics and filters to meet the requirement listed here. These three light sources all have reasonable spectral matches to terrestrial sunlight.

The sunlight simulator should have the following characteristics:

(1) Total irradiance: The simulator must be capable of at least 1000 W/m^2 as measured with a reference solar cell matched to the array or cells to be tested.

(2) Nonuniformity of total irradiance: Nonuniformity of total irradiance is defined (in percent) as

$$\left(\frac{\text{Maximum irradiance - Minimum irradiance}}{2 \times \text{Average irradiance}}\right) \times 100$$

where the maximum and minimum irradiances are in the plane of the test cell or array. The area of the detector must be less than one-quarter of the test cell area or, for the case of ribbon cells, the largest dimension of the detector must be less than one-half of the smallest dimension of the cell being measured. Nonuniformity of total irradiance should be less than 2 percent.

(3) Temporal stability of irradiance: The temporal stability is defined in a similar manner to the nonuniformity of total irradiance. It must be within

2 percent over the period of time required to make cell measurements as determined by a solar cell detector.

(4) Solar beam subtense angle: The angle subtended by the apparent source of the simulator on a point on the test cell must be less than 30°.

6.2 Common Test Equipment

Most of the solar cell tests described previously require essentially identical equipment. The details and specifications of this equipment are listed here.

Reference solar cell readout. - A digital voltmeter, potentiometric recorder, or other suitable measuring instrument capable of measuring with an error less than ±0.5 percent over the 0 to 100 mV range is used to measure reference cell output. If preamplifiers are used to match an automatic data system level, the system must meet the less than ±0.5 percent error requirement as demonstrated by impressing known voltages across an input impedance equal to that of the standard cell device.

Temperature monitoring and control. - Each reference cell holder is fitted with a suitable thermocouple or thermistor, which is used to set temperature at standard conditions. With this sensor the measuring equipment must be capable of 1° C accuracy. Reference cell temperature is to be maintained at $28^{\circ}\pm2^{\circ}$ C.

Test fixture (steady state). - The solar cell to be tested is mounted on a test fixture which has the following features: vacuum holddown, temperature-controlled block, and four terminal contacts (current + and -; voltage + and -).

Cell and array measurement equipment. - Equipment must be capable of measuring the voltage and current of the solar cell over the range between open-circuit voltage and short-circuit current with an error less than 0.5 percent. Short-circuit current must be measured at a voltage less than 20 mV per junction. Open-circuit voltage is measured with a meter having an internal resistance of at least 20 kΩ/V. Instruments such as digital voltmeters and X-Y plotters shall have calibrations which can be traced to a recognized standard.

7.0 TERRESTRIAL SOLAR SPECTRUM

For purposes of theoretical calculations, a revised terrestrial solar spectrum is provided (see fig. 2). Table I gives the spectral irradiance data in W/cm^2-μm for corresponding wavelengths. Also given in table I are the average number of photons/cm^2-sec for wavelength intervals between the corresponding wavelength and the one above it. This spectral distribution of the direct solar beam was calculated using a computer program supplied by Dr. M. Thekaekara. The model starts with an AM0 spectrum and attenuates for various scattering and absorbing processes. The model was revised slightly to allow forward scattering by aerosols. This was done by increasing the transmission of the turbidity term by one-half of the difference between 100 percent and the uncorrected turbidity term. The parameters used in converting the Labs and Neckel AM0 data to terrestrial spectrum are as follows:

Precipitable water, cm	2.00
Ozone, cm	0.34
Air mass	1.5
Aerosol scattering parameters:	
Alpha	1.3
Beta	0.12

REFERENCES

1. Brandhorst, Henry W., Jr., et al.: Interim Solar Cell Testing Procedures for Terrestrial Applications. NASA TM X-71771, 1975.

2. Sandstrom, J. D.: A Method for Predicting Solar Cell Current-Voltage Characteristics as a Function of Incident Solar Intensity and Cell Temperature. Sixth Photovoltaic Specialists Conference, vol. II, Inst. Elect. Electron. Eng., 1967, pp. 199-208.

TABLE I. - REVISED AIR-MASS-1.5 SPECTRAL DISTRIBUTION

Wave-length, μm	Irradiance, $W/(cm^2\text{-}\mu m)$	(Number of photons)/$(sec\text{-}cm^2)$[a]	Wave-length, μm	Irradiance, $W/(cm^2\text{-}\mu m)$	(Number of photons)/$(sec\text{-}cm^2)$[a]
0.295	0	-----------	0.900	807.83	4.5747×10^{15}
.305	1.32	9.9792×10^{11}	.9075	793.87	2.7358×10^{15}
.315	20.96	1.7405×10^{13}	.915	778.97	2.7088×10^{15}
.325	113.48	1.0841×10^{14}	.925	217.12	2.3093×10^{15}
.335	182.23	2.4591×10^{14}	.930	163.72	4.4507×10^{14}
.345	234.43	3.5699×10^{14}	.940	249.12	9.7273×10^{14}
.355	286.01	4.5903×10^{14}	.950	231.30	1.1441×10^{15}
.365	355.88	5.8232×10^{14}	.955	255.61	5.8437×10^{14}
.375	386.80	6.9247×10^{14}	.965	279.69	1.2950×10^{15}
.385	381.78	7.3599×10^{14}	.975	529.64	1.9783×10^{15}
.395	492.18	8.5893×10^{14}	.985	496.64	2.5345×10^{15}
.405	751.72	1.2539×10^{15}	1.018	585.03	9.0087×10^{15}
.415	822.45	1.6264×10^{15}	1.082	486.20	1.8141×10^{16}
.425	842.26	1.7619×10^{15}	1.094	448.74	3.0761×10^{15}
.435	890.55	1.8777×10^{15}	1.098	486.72	1.0335×10^{15}
.445	1077.07	2.1817×10^{15}	1.101	500.57	8.2066×10^{14}
.455	1162.43	2.5396×10^{15}	1.128	100.86	4.5607×10^{15}
.465	1180.61	2.7161×10^{15}	1.131	116.87	1.8592×10^{14}
.475	1212.72	2.8347×10^{15}	1.137	108.68	3.8673×10^{14}
.485	1180.43	2.8948×10^{15}	1.144	155.44	5.3137×10^{14}
.495	1253.83	3.0058×10^{15}	1.147	139.19	2.5515×10^{14}
.505	1242.28	3.1451×10^{15}	1.178	374.29	4.6631×10^{15}
.515	1211.01	3.1530×10^{15}	1.189	383.37	2.4856×10^{15}
.525	1244.87	3.2182×10^{15}	1.193	424.85	9.7029×10^{14}
.535	1299.51	3.3983×10^{15}	1.222	382.57	7.1250×10^{15}
.545	1273.47	3.5013×10^{15}	1.236	383.81	3.3230×10^{15}
.555	1276.14	3.5338×10^{15}	1.264	323.88	6.2418×10^{15}
.565	1277.74	3.6040×10^{15}	1.276	344.11	2.5654×10^{15}
.575	1292.51	3.6919×10^{15}	1.288	345.69	2.6742×10^{15}
.585	1284.55	3.7666×10^{15}	1.314	284.24	5.3696×10^{15}
.595	1262.61	3.7871×10^{15}	1.335	175.28	3.2209×10^{15}
.605	1261.79	3.8169×10^{15}	1.384	2.42	2.9831×10^{15}
.615	1255.43	3.8695×10^{15}	1.432	30.06	5.5317×10^{14}
.625	1240.19	3.8992×10^{15}	1.457	67.14	8.8455×10^{14}
.635	1243.79	3.9436×10^{15}	1.472	59.89	7.0321×10^{14}
.645	1233.96	3.9961×10^{15}	1.542	240.65	7.9947×10^{15}
.655	1188.32	3.9677×10^{15}	1.572	226.14	5.4969×10^{15}
.665	1228.40	4.0195×10^{15}	1.599	220.46	4.8178×10^{15}
.675	1210.08	4.1171×10^{15}	1.608	211.76	1.5719×10^{15}
.685	1200.72	4.1311×10^{15}	1.626	211.26	3.1027×10^{15}
.695	1181.24	4.1418×10^{15}	1.644	201.85	3.0538×10^{15}
.6983	973.53	1.2483×10^{15}	1.650	199.68	9.9992×10^{14}
.700	1173.31	6.4301×10^{14}	1.676	180.50	4.1424×10^{15}
.710	1152.70	4.1324×10^{15}	1.732	161.59	8.2262×10^{15}
.720	1133.83	4.1199×10^{15}	1.782	136.65	6.6025×10^{15}
.7277	974.30	2.9610×10^{15}	1.862	2.01	5.0932×10^{15}
.730	1110.93	8.8089×10^{14}	1.955	39.43	1.8535×10^{15}
.740	1086.44	4.0700×10^{15}	2.008	72.58	2.9643×10^{15}
.750	1070.44	4.0493×10^{15}	2.014	80.01	4.6397×10^{14}
.7621	733.08	4.1577×10^{15}	2.057	72.57	3.3654×10^{15}
.770	1036.01	2.6980×10^{15}	2.124	70.29	5.0424×10^{15}
.780	1018.42	4.0123×10^{15}	2.156	64.76	2.3306×10^{15}
.790	1003.58	3.9999×10^{15}	2.201	68.29	3.2869×10^{15}
.800	988.11	3.9902×10^{15}	2.266	62.52	4.7856×10^{15}
.8059	860.28	2.2067×10^{15}	2.320	57.03	3.7303×10^{15}
.825	932.74	7.0375×10^{15}	2.338	53.57	1.1684×10^{15}
.830	923.87	1.9358×10^{15}	2.356	50.01	1.1027×10^{15}
.835	914.95	1.9288×10^{15}	2.386	31.93	1.5673×10^{15}
.8465	407.11	3.2212×10^{15}	2.415	28.10	9.8088×10^{14}
.860	857.46	3.6707×10^{15}	2.453	24.96	1.2367×10^{15}
.870	843.02	3.7067×10^{15}	2.494	15.82	1.0422×10^{15}
.875	835.10	1.8448×10^{15}	2.537	2.50	5.0182×10^{14}
.8875	817.12	4.5865×10^{15}			

[a]Number of photons/$(sec\text{-}cm^2)$ in the wavelength interval between the corresponding wavelength and the one preceding it. Calculated using the average wavelength and irradiance for each wavelength interval.

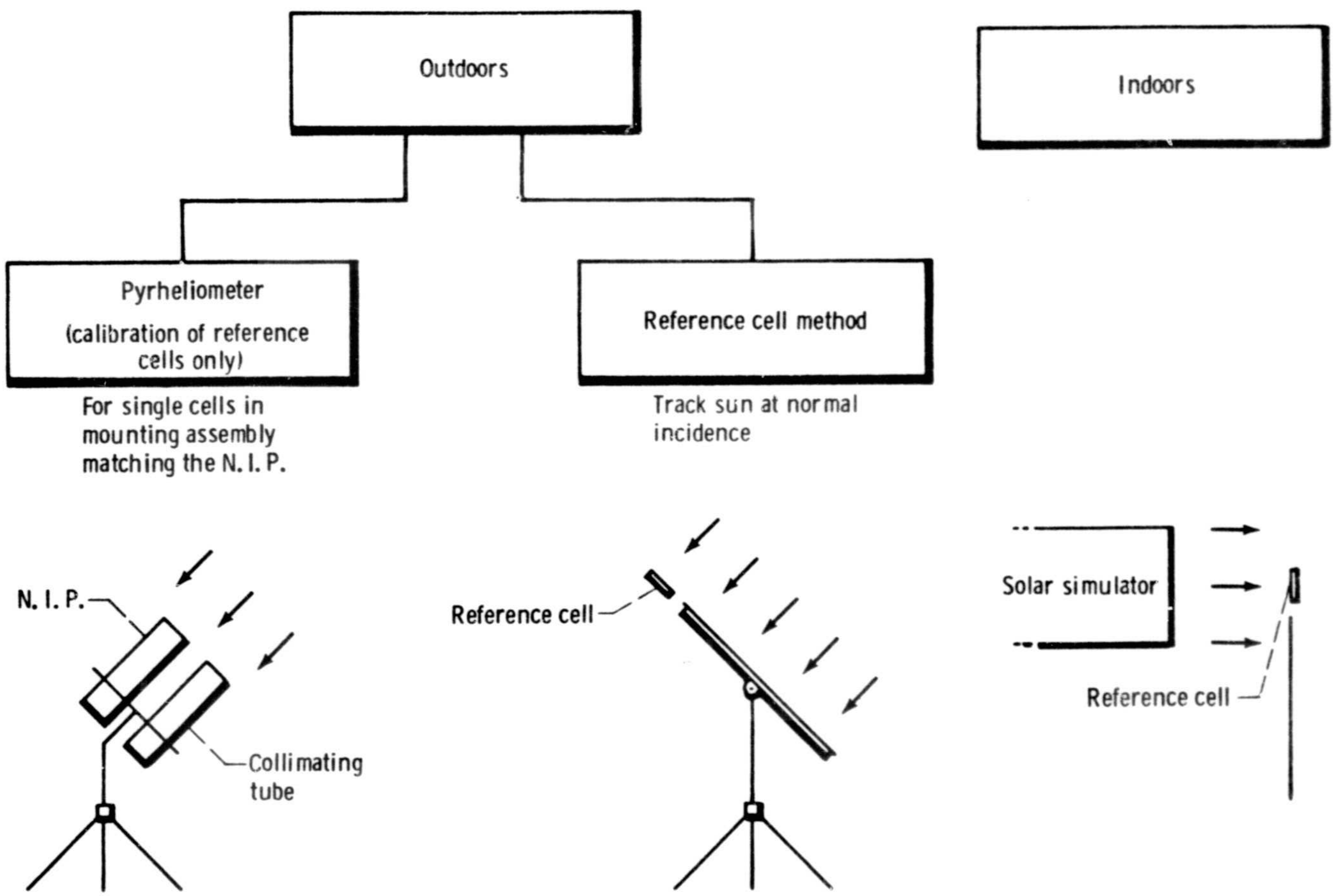
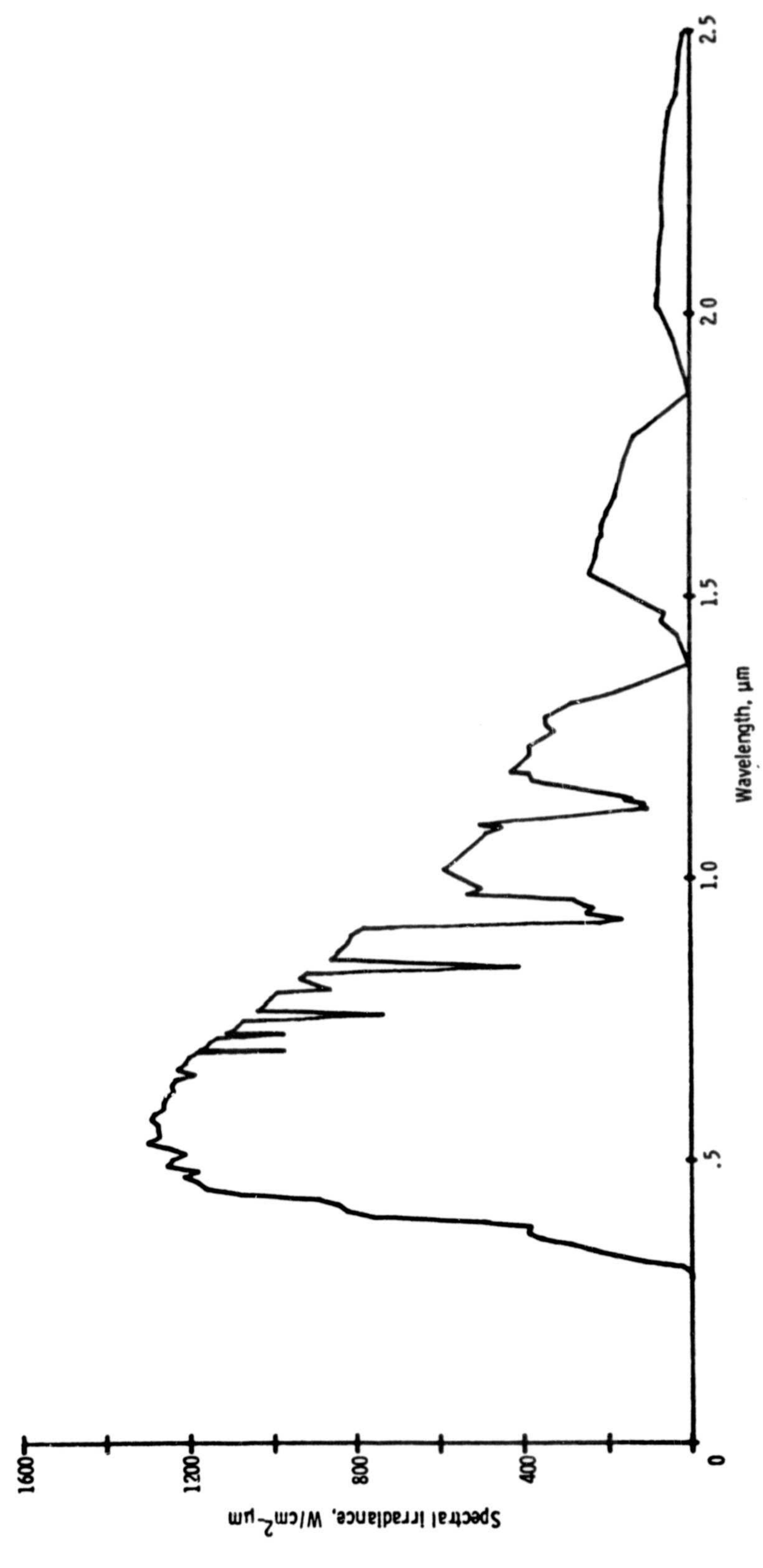

Outdoors
Indoors
Pyrheliometer
(calibration of reference cells only)
Reference cell method
For single cells in mounting assembly matching the N. I. P.
Track sun at normal incidence
N. I. P.
Collimating tube
Reference cell
Solar simulator
Reference cell

Figure 1.



Spectral Irradiance, W/cm^2-µm
1600
1200
800
400
0
.5
1.0
1.5
2.0
2.5
Wavelength, µm

Figure 2.

APPENDIX C

Sample PV Battery Technical Data Sheet

C and D Battery Co.

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DETAILS AND SPECIFICATIONS — TYPE DCP, KCP AND LCP BATTERIES

for SHALLOW DISCHARGE APPLICATIONS with Maximum Reserve Capacity

HOT CLIMATE APPLICATION DATA

For Average Annual Temperatures greater than 90°F (32°C)

Cell Type	AH Capacity at 77°F (25°C) 8 Hr.	100 Hr.	500 Hr.	Dimensions Length in.	Length mm	Width in.	Width mm	Height in.	Height mm	Weight lb.	Weight kg.
2 DCPSD-3	25	42	50	3.59	91	7.38	187	10.31	262	18	8.2
3 DCPSD-3	25	42	50	5.28	134	7.38	187	10.31	262	27	12.2
2 DCPSD-5	50	85	100	6.38	162	7.38	187	10.31	262	33	15.0
3 DCPSD-5	50	85	100	9.47	241	7.38	187	10.31	262	47	21.3
2 DCPSD-7	75	128	150	6.38	162	7.38	187	10.31	262	36	16.3
3 DCPSD-7	75	128	150	9.47	241	7.38	187	10.31	262	53	24.0
DCPSD-9	100	170	200	6.38	162	7.38	187	10.75	273	34	15.4
DCPSD-11	125	212	250	6.38	162	7.38	187	10.75	273	36	16.3
DCPSD-13	150	255	300	6.38	162	7.38	187	10.75	273	38	17.2
KCPSD-5	180	306	360	3.63	92	10.44	265	18.25	464	49	22.2
KCPSD-7	270	459	540	4.63	118	10.44	265	18.25	464	76	34.5
KCPSD-9	360	612	720	6.59	167	10.44	265	18.25	464	94	42.6
KCPSD-11	450	765	900	8.53	217	10.44	265	18.25	464	118	53.5
KCPSD-13	540	918	1080	8.53	217	10.44	265	18.25	464	142	64.4
4 LCPSD-5	336	561	660	15.00	381	14.13	359	22.62	575	290	131.5
LCPSD-11	840	1402	1650	7.63	194	14.13	359	22.62	575	188	85.3
LCPSD-13	1008	1683	1980	8.63	219	14.13	359	22.62	575	220	99.8
LCPSD-15	1176	1963	2310	10.63	270	14.13	359	22.62	575	260	117.9
LCPSD-17	1344	2244	2640	13.19	335	14.13	359	22.62	575	299	135.6
LCPSD-19	1512	2524	2970	13.19	335	14.13	359	22.62	575	316	143.3

Recommended Charge Voltage — 2.38 to 2.42 volts/cell @ 77°F (25°C)
Specific Gravity at 77°F (25°C) — Full Charge 1.225
Specific Gravity at 77°F (25°C) 100% Discharge — 1.040 @ 500 Hour Rate
Final Voltage at 500 Hr. Capacity — Approximately 1.95 volts per cell
Self-discharge Rate — 1% per month @ 77°F (25°C), 6% @ 130°F

NORMAL AND COLD CLIMATE APPLICATION DATA

For Average Annual Temperatures less than 90°F (32°C)

Cell Type	AH Capacity 8 Hr. 77°F (25°C)	100 Hr. 77°F (25°C)	500 Hr. 77°F (25°C)	500 Hr. 32°F (0°C)	500 Hr. 0°F (-18°C)	Dimensions Length in.	Length mm	Width in.	Width mm	Height in.	Height mm	Weight lbs.	Weight kg.	Max. AH to 0°F FP*
2 DCPSA-3	31	42	50	45	36	3.59	91	7.38	187	10.31	262	18.4	8.3	50
3 DCPSA-3	31	42	50	45	36	5.28	134	7.38	187	10.31	262	27.7	12.6	50
2 DCPSA-5	62	73	75	68	55	3.59	91	7.38	187	10.31	262	22.6	10.3	67
3 DCPSA-5	62	73	75	68	55	5.28	134	7.38	187	10.31	262	33.6	15.2	67
2 DCPSA-7	94	128	150	134	109	6.38	162	7.38	187	10.31	262	36.9	16.7	139
3 DCPSA-7	94	128	150	134	109	9.47	241	7.38	187	10.31	262	54.3	24.6	139
2 DCPSA-9	125	140	145	129	105	6.38	162	7.38	187	10.31	262	40.8	18.5	128
3 DCPSA-9	125	140	145	129	105	9.47	241	7.38	187	10.31	262	61.2	27.8	128
DCPSA-11	156	212	250	224	182	6.38	162	7.38	187	10.75	273	37	16.8	250
DCPSA-13	188	255	300	268	218	6.38	162	7.38	187	10.75	273	39	17.7	286
DCPSA-15	219	300	310	276	225	6.38	162	7.38	187	10.75	273	41	18.6	274
DCPSA-17	250	286	295	264	215	6.38	162	7.38	187	10.75	273	42	19.1	261
2 KCPSA-5	225	289	340	306	249	5.59	142	10.44	265	18.25	464	88	39.9	304
3 KCPSA-5	225	289	340	306	249	8.53	217	10.44	265	18.25	464	131	59.4	304
KCPSA-7	337	358	400	336	293	3.62	92	10.44	265	18.25	464	58	26.3	357
KCPSA-9	450	509	525	471	384	4.62	117	10.44	265	18.25	464	79	35.8	467
KCPSA-11	562	625	645	579	471	5.59	142	10.44	265	18.25	464	96	43.5	574
KCPSA-13	675	747	770	690	561	6.59	167	10.44	265	18.25	464	113	51.3	684
KCPSA-15	787	1023	1055	951	774	8.53	217	10.44	265	18.25	464	139	63.0	943
KCPSA-17	900	992	1023	891	725	8.53	217	10.44	265	18.25	464	146	66.2	909
4 LCPSA-5	420	518	535	479	390	10.14	258	14.12	359	22.62	575	276	125.2	474
4 LCPSA-7	630	795	820	734	597	15.00	381	14.12	359	22.62	575	391	177.4	727
LCPSA-11	1050	1402	1650	1476	1202	7.62	194	14.12	359	22.62	575	188	85.3	1577
LCPSA-13	1260	1649	1700	1521	1238	7.62	194	14.12	359	22.62	575	205	93.0	1508
LCPSA-15	1470	1571	1620	1451	1182	7.62	194	14.12	359	22.62	575	222	100.7	1439
LCPSA-17	1680	1867	1925	1723	1403	8.62	219	14.12	359	22.62	575	254	115.2	1707
LCPSA-19	1890	2308	2380	2132	1735	10.62	270	14.12	359	22.62	575	294	133.4	2113
LCPSA-21	2100	2231	2300	2061	1678	10.62	270	14.12	359	22.62	575	310	140.6	2042
LCPSA-23	2310	2880	2970	2658	2163	13.19	335	14.12	359	22.62	575	353	160.1	2364
LCPSA-25	2520	2803	2890	2589	2107	13.19	335	14.12	359	22.62	575	370	167.8	2565

Recommended Charge Voltage — 2.45 to 2.49 volts per cell @ 77°F (25°C)
Specific Gravity at 77°F (25°C) — Full Charge — 1.300
Specific Gravity at 77°F (25°C) — 100% Discharge — 1.130 @ 500 Hour Rate
Specific Gravity at 32°F (0°C) — 100% Discharge — 1.180 @ 500 Hour Rate
*Electrolyte will not freeze if these values are not exceeded.

C&D BATTERIES DIVISION
3043 WALTON ROAD, PLYMOUTH MEETING, PA 19462
an Eltra company

C&D BATTERIES OF CANADA
P.O. BOX 276, PERTH, ONTARIO K7H 3E4
an Eltra company

7.5M/279

Printed in U.S.A.

SAFETY RULES FOR MAINTAINING LEAD-ACID BATTERIES

Observe these simple, common sense suggestions, when working around storage batteries to help prevent injuries to personnel and damage to batteries and equipment.

CAUTION	REASON
1. Keep open flames and spark-producing sources away from storage batteries.	*Hydrogen may be entrapped in the battery. A flame or spark can cause an explosion, although flame arrestors greatly reduce the probability.*
2. Shut off and disconnect the charger from both the input source and output connection before repairing charging equipment.	*Possible damage to the charging equipment and electrical shock to the individual will be reduced.*
3. Never lay metal tools on top of a battery.	*Sparking and short circuits can occur.*
4. Wear rubber apron, gloves, boots and facemasks —when handling, checking, filling, charging or repairing batteries.	*For protection against accidental spillage of electrolyte—a mixture of sulfuric acid and water . . . could cause a painful burn.*
5. Always have fresh water available in case electrolyte is splashed on skin, clothing or EYES. If electrolyte is splashed into eyes, flush eyes with water from a safety fountain or cold water tap and immediately SEE A DOCTOR.	*Volumes of water applied quickly and continuously may prevent serious injury to the skin and possibly avert permanent eye damage.*
6. Brush on a neutralizing solution, such as baking soda and water, when acid is spilled on the floor, and clean up promptly. A mixture of one pound baking soda to one gallon of water is recommended.	*Mild alkali will neutralize the acid and make it safe to clean or flush from the floor.*
7. Wear protective clothing and goggles when mixing acid and water . . . Always ADD ACID CAREFULLY TO WATER and stir constantly to mix well when preparing electrolyte.	*If water should be added to high specific gravity acid, considerable heat and a violent reaction occur, possibly splashing the handler.*
8. Lift batteries with mechanical equipment, such as hoist, crane or lift truck. Move batteries horizontally with power trucks, conveyors or rollers. Safety shoes and "hard hats" are recommended for handler's protection. Metallic safety hats should be avoided.	*Batteries are a heavy, concentrated load and can easily cause painful strains or injury to handler's back, hands, face or feet. Batteries may be damaged if dropped.*
9. Make sure that battery connections are tight.	*A loose connection can cause sparking or arcing or a high-resistance connection. Sparking or arcing can result in an explosion if sufficient hydrogen gas is present. (Note: Flame arrestors greatly reduce the probability.)*
10. The battery charging area should be a restricted area with adequate ventilation and no-smoking signs posted. Never use sulfuric acid solutions of over 1.400 specific gravity.	*Flames, sparks or arcing can result in an explosion if sufficient hydrogen gas is present. Although all acid solutions must be handled carefully, extreme care must be taken in handling sulfuric acid solutions exceeding 1.400 specific gravity.*
11. Check batteries for acid leakage or signs of corrosion.	*Loss of electrolyte will lower battery capacity and cause shorts to the rack and ground circuitry.*

Familiarize yourself with battery fundamentals and the proper rules for their charging, handling and maintenance. Full knowledge of basic battery technology greatly reduces the probability of injury to the handler and damage to the equipment.

APPENDIX D

SITE INSPECTION CHECKLIST GABON

1. Site Location
   Local du Site

   A. Background Information
      Renseignements sur le Pays

   B. Translator
      Interprete

2. General
   Reseignements Generaux

   A. Personnel Medical Preparation
      Preparation Medicale du Personnel

      (1) Immunizations
          Immunisations

   B. Climatic Data
      Donnee du Limat

      (1) Insolation
          Insolation

      (2) Wind Velocities
          Velocite du Vent

      (3) Temperature Extremes
          Extremes de Temperature

      (4) Rainy Periods
          Periodes de Pluie

      (5) Violent Weather Types
          Genres de Temps Violents
          (tel que le typhon etc.)

   C. Site Codes
      Codes du Site

      (1) Electrical
          Electrique

      (2) Building
          Batiment

      (3) Other
          Autres

D. Maps (Before Site Visit)
Cartes (Avant la Visite du Site)

3. Administrative
Renseignements Administratifs

A. Funding Amounts
Montant des Fonds

(1) Host Country
Pays du Projet

(2) NASA-DOE-AID
NASA-DOE-AID

B. Logistics
Logistique (Transport du Materiel)

C. Construction
Construction

(1) Buildings
Batiments

(2) Well
Puits

(3) Water Tank
Reservoir a Eau

(4) Distribution Systems
Systeme de Distribution

a. Water
Pour L'Eau

b. Electricity
Pour L'Electricite

(5) Labor
Main D'Oeuvre

(6) Materials
Materiaux

4. Site Visit
Visite du Site

A. Site Location
Local du Site

B. Communications
Communications

C. Site Plans Available
Plans du Site Disponibles

(1) Roads
Routes

(2) Buildings (of interest)
Batiments

a. Floor Plans
Plans

b. Drawings
Schema

c. Exterior Dimensions
Dimensions Exterieures

d. Roof Types
Genres de Toît

e. Construction Materials
Materiaux de Construction

f. Pictures Taken
Photos Prises

g. Maps Drawn
Cartes Preparees

h. Building Sizes, Locations, Map Identification
Grandeur et Local des Batiments

D. Water
Eau

(1) Existing Wells
Murs en Existence

a. Depth and Type
Profondeur et Genre

b. Method for Drawing Water
Methode Pour Tirer L'Eau

(2) Water Tank
Reservoir a Eau

a. Type
Genre

b. Size
Taille

(3) Water Distribution
Distribution de L'Eau

a. Plumbing
Plomberie

b. Hydrants
Bouches D'Incendie

c. Commercial Access
Acces Pour La Communaute

d. Usage (l/day)
Eau Employee (litres Par Jour)

E. Other Available Water
Autres Sources D'Eau

(1) Streams/Ponds
Cours D'Eau/Etangs

(2) Dry/Wet Seasons
Saisons - Seches
Saisons - Pluvieuses

(3) Drainage
Ecoulements

F. Electrical
Electricite

(1) Electrification Plans
Projets D'Electrification

(2) Existing Service
Service en Existence

a. Where (houses, clinics, entire village)
Ou (maisons, cliniques, village entier)

b. Distribution System
Systeme de Distribution

1) Voltage
Voltage

2) Amperage
Ampere

3) Breakers
Interrupteur

4) Wiring
Position des Fils Electriques

G. Clinical Loads
Charge Electrique Pour Clinique

(1) Requirements
Besoins

a. Refrigerator/Freezer (Medical Storage only)
Refrigerateur/Congelateur (Pour Storage Medical Seulement)

b. Lighting
Eclairage

1) Examining Area (Size)
Sale D'Examer Medical (Grandeur de la Salle)

2) Other Areas
Autres Endroits

c. Hot Water
Eau Chaude

d. Sterile Water
Eau Sterilisee

e. Space Heating
Espace a Chauffer

H. Clinical Services Provided
Services Rendus a La Clinique

(1) Immunization
Immunisation

(2) Dental
Soins Dentaires

(3) Surgical
Chirurgie

(4) Maternity
Maternite

(5) Area of Service
Local De Service

a. Kilometers from Village
A Combien de Kilometres du Village

b. Number of People in Area
Nombre de Personnes Dans Cette Region

I. Clinical Residences
Residences Attachees a La Clinique

(1) Number
Nombre (Combien)

(2) Loads
Charges

J. Other Loads
Autres Charges Electriques

(1) Laundry
Blanchisserie

(2) Kitchen
Cuisine

K. Schools
Ecoles

(1) Number of Children
Nombre D'Enfants

(2) Schedule
Programme

a. Days
Jours

b. Hours
Heures

c. Months
Mois

(3) Load Requirements
Besoins de Charge - Electrique

a. Lights
Pour L'Eclairage

1) Day (Educational)
Dans la Journee (Education)

2) Night (Community and Educational)
Pe Soir (Affaires de Communaute, Education)

b. Refrigerator
Refrigerateur

1) Upright (size)
Vertical (Taille)

2) Chest (Size)
Horizontal (Genre Malle)(Taille)

c. Water
Eau

d. Educational Aids
Assistance Pour L'Education

1) Existing National Program
Programme National en Existence

2) Types
Genres

I. Government Buildings
Batiments Gouvernementaux

(1) Number
Nombre

(2) Electrical Loads
Charges Electriques

a. Lights
Eclairage

b. Radio
Radio

1) Power Profile (Standby/Transmit)
Puissance (Radio a Deux Voies)

c. Other
Autres

M. Transportation/Logistics

(1) Port of Entry
Port D'Entre

a. Storage Available
Local D'Emmagasinage Disponible

(2) Transportation to Site
Transport Jusquau Site

a. Distance from Entry Port
Distance Du Port D'Entre

b. Type of Delivery (Truck, Plane)
Genre De Livraison (Par Camion, Avion)

c. Estimated Transport Time
Temps De Transport Estime

d. Site Storage Available
Local D'Emmagasinage Disponible Sur Le Site

(3) Construction Requirements
Besoins Essentiels A La Construction

a. Labor Available
Main D'Oeuvre Disponsible

b. Provide Power (Portable Generator)
Il Ya-T-Il Puissance
Electrique ou Doit-on Emmener un Generateur

APPENDIX E

Installation and Maintenance Manual

TABLE OF CONTENTS

Section	Title and Contents	Page
1.0	General	2
2.0	Unpacking and Assembly	2
3.0	Testing	3
	Test 3-1: Solar Array Performance	
	Test 3-2: Blocking Diode Performance	
	Test 3-3: Battery Self-Discharge	
4.0	Maintenance	5
	4.1 Regular Maintenance	
	4.2 Troubleshooting Guide	
	4.3 Module and Diode Replacement	
5.0	Tools and Equipment	6
	5.1 Installation and Maintenance Tools	
	5.2 Testing Equipment	

INSTALLATION DATA

Site Location: ______

Tilt Angle: ______ Regulator: BVR ______ Design Load: ______ AH/day

Battery: Model ______ connected ______ cells in series by ______ banks in parallel

THE FOLLOWING QA TEST DATA PERTAINS TO YOUR SOLAR ELECTRIC GENERATOR:

Array Performance

Array Model: ______ Serial #: ______

Rated Output* ______ Amps at ______ Volts

Rated Short Circuit Current*: ______ Amps

No. of Series-Connected Solar Cells: ______

No. of Parallel-Connected Solar Cells: ______

Frame Performance

No. of Separate Frames in Array: ______

______ Model M ______ modules on ______ frame(s)

Rated Short Circuit Current* of frame(s): ______ amps ea

______ Model M ______ modules on ______ frame(s)

Rated Short Circuit Current* of frame (s): ______ amps ea.

Module Performance

MODEL M ______ module

Rated Short Circuit Current*: ______ Amps

No. of Series-Connected Solar Cells: ______

No. of Parallel-Connected Solar Cells: ______

MODEL M ______ module

Rated Short Circuit Current*: ______ Amps

No. of Series-Connected Solar Cells: ______

No. of Parallel-Connected Solar Cells: ______

*At 100mW/ cm^2 sunlight intensity and 28°C cell temperature.

Solar Power Corporation

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1.0 GENERAL

1.1 This manual includes the unpacking, assembly, and maintenance instructions for the Solar Power Corporation Solar Electric Generator Series M Arrays. For information relating to the installation and maintenance of the storage battery system, refer to Manufacturer's Instructions.

1.2 Properly installed solar electric generator systems should only require regular maintenance visits once a year. Maintenance recommendations are given in Section 4.1.

1.3 If any trouble does develop, Sections 3.0 and 4.0 give complete test, troubleshooting, and repair procedures. If additional help is required, contact the Technical Service Department at Solar Power Corporation.

2.0 UNPACKING AND ASSEMBLY INSTRUCTIONS

2.0.1 Because the arrays may be anchored to different types of mounting surfaces, the customer is expected to supply mounting hardware.

2.0.2 If the total array consists of more than one frame, repeat all instructions for each frame.

2.1 UNPACKING AND ASSEMBLY - ARRAYS WITH TELESCOPING LEGS

2.1.1 Open the crate. Remove the layer of packing material and any other hardware or items that are on top of the array.

2.1.2 Lift the array out of the crate and hold it nearly vertical or place it on the ground, front module surface facing up. DO NOT PUT THE ARRAY ON THE GROUND FACING DOWN.

2.1.3 Unbolt the mounting feet from the leg sections. Retain this hardware and all other hardware removed in the following steps; it will be needed to assemble the legs and mounting feet to the array frame (reference Figure 1b).

2.1.4 Unbolt the two large leg sections (larger cross sectional area) from the bottom mounting brackets. Attach one mounting foot to one end of each of these leg sections as shown in Figure 1, Point C. It may be necessary to loosen the bolt holding the small leg to the top mounting bracket, thus allowing the leg to swing.

2.1.5 Attach the remaining two mounting feet to the bottom mounting brackets (the ones that do not have leg sections attached to them) as shown in Figure 1, Point D.

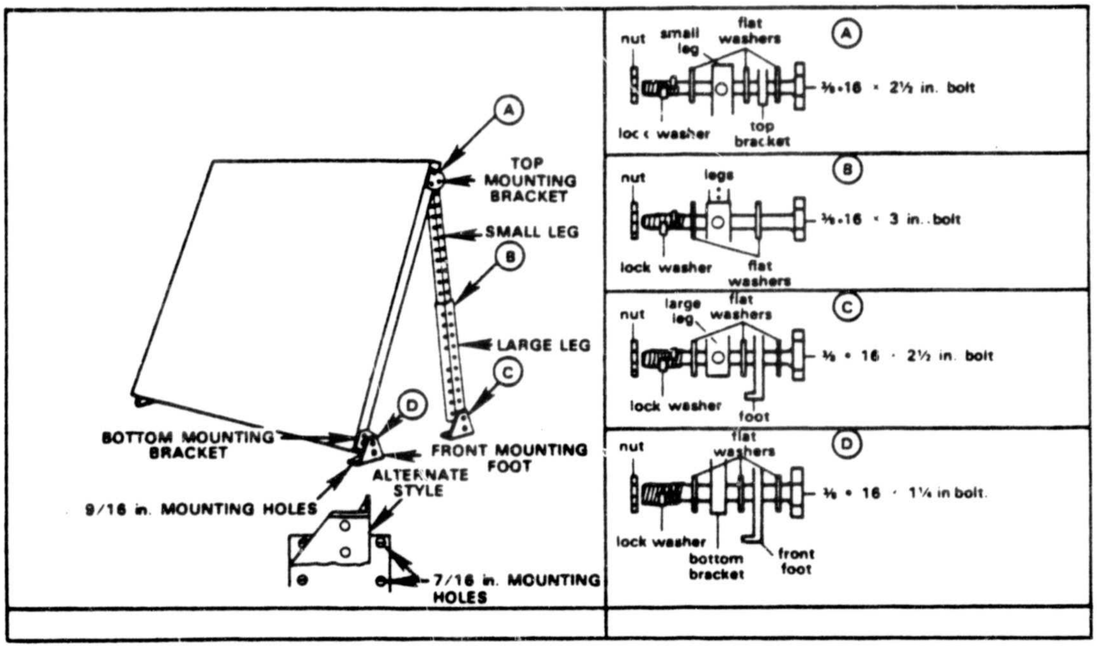
2.1.6 The array is now fully assembled and ready to be moved to its installation location and oriented. If the array must be disassembled or recrated, reverse the above procedure.

2.2 ORIENTING THE ARRAY - ARRAYS WITH TELESCOPING LEGS

2.2.1 When selecting a mounting location, make sure that the bottom of the array will be at least 3 feet (or 1 meter) higher than the maximum snow depth level.

2.2.2 IMPORTANT: THE ARRAY MUST BE ALIGNED SUCH THAT THE FRONT (MODULE) SURFACE DIRECTLY FACES DUE SOUTH (DUE NORTH IN THE SOUTHERN HEMISPHERE). WHEN USING A MAGNETIC COMPASS MAKE SURE TO CORRECT FOR THE LOCAL DIFFERENCE BETWEEN MAGNETIC DIRECTION AND TRUE DIRECTION. Anchor the front mounting feet once the array is aligned.

FIGURE 1



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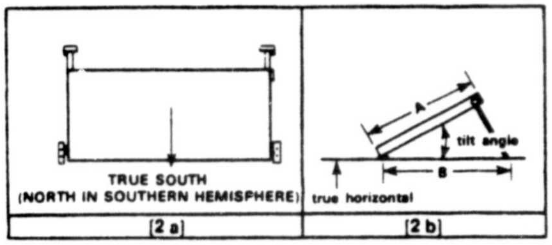
2.2.3 Anchor the legs' mounting feet to the mounting surface. It is best to make support spacing (B) equal to array dimension (A) (reference Figure 2b). Other positions may be used as necessary depending on the angle required and/or terrain considerations.

2.2.4 To set the tilt angle of the array, remove the long bolts anchoring the leg sections together (reference Figure 1, Point B) and adjust the length of the telescoping legs. The tilt angle of the array (the angle the array surface makes with a horizontal surface) should be adjusted to within 2 degrees of the specified angle. An inclinometer (adjustable angle liquid level) is most useful in measuring this angle, although, with care, a protractor and an ordinary bubble level may also be used. Reinsert the bolts and tighten.

2.2.5 Tighten all nuts and bolts.

FIGURE 2



2.3 ATTACHMENT OF CABLES

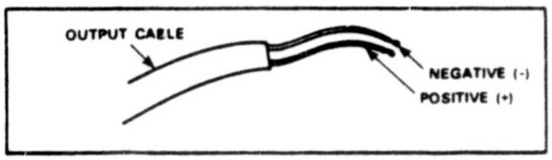
2.3.1 If a battery voltage regulator is included in the system or if one is added to the system, follow the instructions included with the regulator.

2.3.2 **Single Frame Arrays:** The output cable can be attached directly to the battery. Observe the correct polarity; black is positive, white is negative (reference Figure 4). If the polarity is accidentally reversed, no damage will result to either the array or the battery (assuming the battery is of the proper voltage for the array). However, if the polarity is left reversed for more than a few hours, the solar electric generator system will not function and the battery may become discharged.

2.3.3 **Multiframe Arrays:** Each frame is supplied with a separate output cable. Attach the output cable directly to the appropriate battery terminal (observe correct polarity).

2.3.4 After connecting cable(s) to the battery and connecting any required battery intercell connecting wires, protect all battery terminals from corrosion with a layer of grease.

FIGURE 3



3.0 TESTING

There are several tests that can be conducted to check system performance: Test 3-1 (Solar Array Performance), Test 3-2 (Blocking Diode Performance), Test 3-3 (Battery Self-Discharge). These can be performed either independently or in conjunction with the Troubleshooting Guide, Section 4.2.

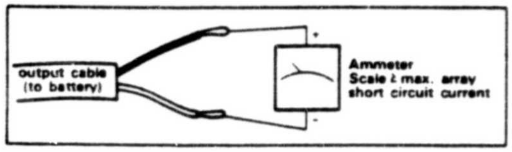
Upon installation, Test 3-1 (Solar Array Performance) should be conducted. Tests 3-2 and 3-3 should be performed if trouble occurs.

The annual maintenance visit can include the following simple check of the solar electric generator system performance. Measure the specific gravity of the battery electrolyte (for lead-acid batteries) with a standard battery hydrometer. Correct the readings to 77°F (25°C) using Table 3-1. Refer to Table 3-2 and relate the percent of battery capacity remaining to the corrected electrolyte specific gravity. If battery electrolyte specific gravity is low, refer to Section 4.2, Conditions 1 and 2.

TEST 3-1: SOLAR ARRAY PERFORMANCE

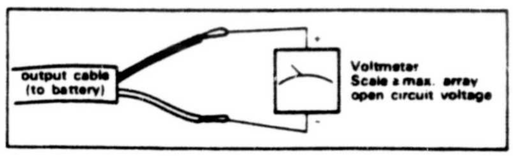
1. This test must be performed during the middle hours of a sunny day. The sun must be clearly visible with no thick haze present.
2. Disconnect array cable(s) or voltage regulator-battery cable from the battery terminals. If the system contains a regulator(s), disconnect regulator(s) following instructions provided with regulator(s) before proceeding to the next step.
3. Connect a suitable ammeter across the two disconnected cable leads (reference Figure 4). The ammeter's resistance should be such that the voltage drop across the ammeter is less than 0.3 volt. Adjust the tilt angle of the array to obtain the maximum current output as indicated by the ammeter.

FIGURE 4



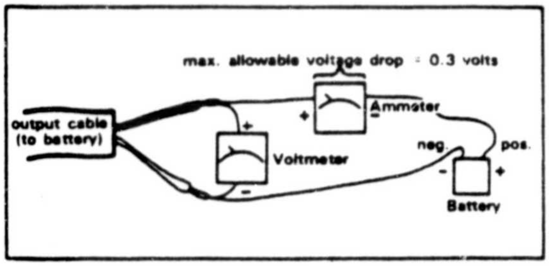
4. The ammeter current reading (short circuit current) should be approximately 70% of the 100mW/cm^2 short circuit current (listed under "Array Performance" on the front cover).
5. Disconnect the ammeter. Connect across the same cable leads (reference Figure 5) a voltmeter having an impedance of at least 1,000 ohms per volt. The voltmeter reading (open circuit voltage) should be greater than 0.48 volt times the total number of solar cells in series (listed under "Array Performance" on the front cover).

FIGURE 5



6. Disconnect the voltmeter. Reconnect the negative lead to the battery. Connect an ammeter between the positive cable lead and the positive battery terminal (positive ammeter lead to the positive cable lead). Connect the voltmeter to the two cable leads (reference Figure 6). If this voltage is less than 2.2 volts times the number of series-connected lead-acid battery cells, the measured current should be at least 80% of the current measured in Step 4 (assuming sunlight conditions unchanged since Step 3).

FIGURE 6



7. For multiframe arrays this test procedure can be repeated for each individual array section by making these tests at each individual array cable termination. For each individual array section, disconnect the cable leads from the terminal block inside the external junction box and repeat Steps 3 through 6. The corresponding information for each frame is listed on the front cover of this manual (reference "Frame Performance").

8. If an array does not pass this test, refer to the Trouble-shooting Guide, Section 4.2.

TABLE 3-1

HYDROMETER READING CORRECTIONS TO 77°F

Electrolyte Temperature (°F)	Correction (add to reading)
140	+0.024
130	+0.020
120	+0.016
110	+0.012
100	+0.008
90	+0.004
80	+0.000
70	-0.004
60	-0.008
50	-0.012
40	-0.016
30	-0.020
20	-0.024
10	-0.028
0	-0.032
-10	-0.036
-20	-0.040
-30	-0.044
-40	-0.048

NOTE: The temperature of the electrolyte solution, not the ambient air temperature, should be measured with an immersion type thermometer. Some hydrometers have a thermometer and temperature correction scale built in.

TABLE 3-2

PERCENT OF 500 HOUR RATE CAPACITY REMAINING
vs.
ELECTROLYTE SPECIFIC GRAVITY (CORRECTED TO 77°F)

	Initial Electrolyte Specific Gravity		
	1.210	1.250	1.300
% Capacity Remaining	Hydrometer Reading (Corrected to 77°F)		
100	1.210	1.250	1.300
90	1.197	1.235	1.283
80	1.185	1.221	1.266
70	1.172	1.206	1.249
60	1.160	1.192	1.232
50	1.147	1.177	1.215
40	1.135	1.163	1.198
30	1.122	1.148	1.181
20	1.110	1.134	1.164
10	1.097	1.119	1.147
0	1.085	1.105	1.130

TEST 3-2: BLOCKING DIODE PERFORMANCE

1. This test must be performed either at night with no artificial light striking the array or with a black opaque cloth covering the entire array (reference Figure 7).

2. Disconnect the positive lead of the array cable(s) or the voltage regulator-battery cable from the battery terminals. Connect a milliammeter between this disconnected lead and the positive battery terminal (positive milliammeter lead to the positive battery terminal) (reference Figure 7). The current measured should be less than 4mA times the number of solar cells connected in parallel (listed under "Array Performance" on the front cover).

3. A current exceeding the above value indicates that the diode(s) has developed excessive reverse leakage current. If the array contains a diode mounted in a junction box, it should be replaced (reference Section 4.3). If the system includes a voltage regulator(s), refer to Regulator Manual for testing procedure. Otherwise, the diode(s) is located inside the module(s) and this test should be repeated for each module on the affected frame. Access to each module's leads may be obtained by removing the attached junction box cover. Disconnect the leads at the terminal block before starting the test. Remember that no light can strike the module's surface. Diodes located in the terminal box attached to the back of each module are sealed and cannot be replaced in the field. Any module that shows excessive reverse leakage current should be replaced (reference Section 4.3).

TEST 3-3: BATTERY SELF-DISCHARGE (LEAD-ACID BATTERIES)

NOTE: THIS TEST WILL REQUIRE REMOVAL OF THE BATTERY SYSTEM FROM THE ARRAY SITE.

1. Disconnect all cables from the battery terminals. Charge the battery or battery cell at a current rate not exceeding the battery's capacity in ampere hours divided by 20 hours (e.g., a 100-ampere hour battery would be charged at a current of 5 amperes or less). A standard battery charger should suffice for this purpose. Discontinue charging when the battery's terminal voltage exceeds 2.3 volts per series-connected battery cell.

2. Take a specific gravity reading of the electrolyte in each battery cell and record the corrected values (use Table 3-1 and an immersion thermometer).

3. Allow the battery to stand idle at room temperature for a week. At the end of the week take a second set of specific gravity readings. Compare with readings taken in Step 2. Corrected readings differing by more than 15 points (0.015) indicate a battery cell with excessively high self-discharge.

4.0 MAINTENANCE

4.1 REGULAR MAINTENANCE

(Yearly intervals recommended.)

4.1.1 Check battery electrolyte level. Replenish with distilled water, if necessary. When checking or adding to the battery electrolyte, the battery manufacturer's recommendations should be followed.

4.1.2 Check the module surface(s) for dirt buildup. Normal rainfall will usually be sufficient to provide for self-cleaning if the array is tilted at 15° or more from the horizontal. However, if dirt buildup becomes excessive, either plain water or a mild detergent solution followed by a water rinse **may be used. DO NOT USE SOLVENTS OR STRONG DETERGENTS.**

4.2 TROUBLESHOOTING GUIDE

Most problems can be isolated with the aid of the following guide. If it is impossible to locate the problem, please contact the Technical Service Department at Solar Power Corporation for assistance.

SYMPTOM	Other Symptoms
Battery electrolyte specific gravity low (lead-acid batteries)	Specific gravities of all battery cells differ no more than 20 points (0.020)

Checks and Repairs

1. Check all battery electrical connections for corrosion and mechanical soundness. Clean and/or repair.
2. Check to see if there are any obstructions that shadow any portion of the array during any part of the day. If this condition exists, either the obstruction must be removed or the array must be moved to an unobstructed location.
3. Check the orientation of the array. Make sure it is facing directly due south (north in the southern hemisphere) and the tilt angle is correct (reference Section 2.2 or 2.3).
4. Check the load current. Calculate the equivalent number of amp hours per day required by the load. Compare this calculation against the design load listed under "Installation Data" on the front cover. If the measured load exceeds the design load, contact the Technical Service Department at Solar Power Corporation. Each solar electric generator system is designed for a specific load. Deviations from that load may result in unsatisfactory operation.
5. Check the solar array output by following the instructions in Test 3-1. Refer to Conditions 3, 4, 5, or 6 (Section 4.2) as necessary.
6. Check the blocking diode(s) by following the instructions in Test 3-2.
7. Check for high battery self-discharge by following the instructions in Test 3-3. If the battery or part of the total battery system fails this test, replace the defective battery cell(s).

SYMPTOM	Other Symptoms
Same as Condition 1	Specific gravity of only one or a few battery cells low

Checks and Repairs

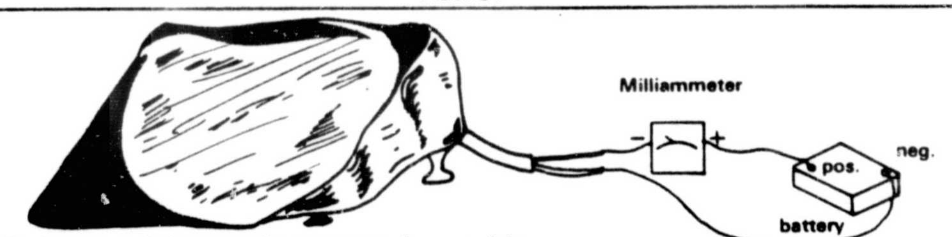
1. Check for excessively high electrolyte level. If so, shelter battery to prevent rain from entering through the vent hole(s).
2. Check the affected cells for high battery self-discharge by following the instructions in Test 3-3. Replace battery cell or battery containing bad cell.

SYMPTOM
Array open circuit voltage equal to zero (from Test 3-1)

Checks and Repairs

1. Single Frame Arrays:
   (a) If the array consists of only one module, that module must be replaced (reference Section 4.3).
   (b) If the array consists of more than one module, remove the cover of the junction box mounted to the back of the array. With the output cable disconnected from the battery terminals, test for voltage at the individual module leads. If voltage is present, there are bad contacts. At the terminal block, or the crimp connectors attached to the output cable are not making contact to the wire, or the output cable's conductors are broken. Clean all connections. Test crimp connectors by pulling on wires. Recrimp or attach wire directly to terminal block if necessary. Test the cable with an ohmmeter or continuity tester. Replace output cable if it is an open circuit.
2. Multiframe Arrays:
   (a) Remove junction box cover. Check for loose connections at the terminal block. Tighten if necessary.

FIGURE 7



Black opaque cloth over entire array or perform at night with no light shining on array.

Solar Power Corporation

(b) Test for voltage at the individual array cable terminations. If voltage is present there, proceed to Step 2 (c). If no voltage is present at any of the cable terminations, each array section must be checked individually as described in Step 1(b).

(c) Make sure that at least one lead of the battery cable is disconnected from the battery terminals. Connect a jumper wire between any positive array cable terminal and the positive battery cable terminal. If voltage is now present at the battery cable leads, and there is a blocking diode within an external junction box, either the blocking diode is defective or one of the wires connecting the diode to the terminal block is broken. Detach the plate on which the terminal block is mounted by removing the four corner screws. The blocking diode is located beneath the plate. Inspect for any broken wires and if none are found, replace the diode (reference Section 4.3).

(d) Check the continuity of the battery cable with an ohmmeter or continuity tester. Replace output cable if it is an open circuit.

SYMPTOM

Array open circuit voltage low (from Test 3-1)

Checks and Repairs

1. Check that the voltmeter's resistance is greater than 1,000 ohms per volt, that the sun is clearly visible, that there is no thick haze blocking the sun, and that the array is aimed towards the sun.

2. Single Frame Arrays:
   (a) If the array consists of only one module, that module should be replaced (reference Section 4.3).

2. (b) If the array consists of more than one module, remove the cover of the junction box mounted in the back of the array. Disconnect the cable leads from each module. Test each module individually for low open circuit voltage. The voltmeter reading (open circuit voltage) should be greater than 0.48 volt times the number of solar cells in series (listed under "Module Performance" on the front cover). Any module that does not pass this test should be replaced (reference Section 4.3).

3. Multiframe Arrays: Disconnect the array cables from the terminal block in the external junction box or from the battery terminals. Check the open circuit voltage at each individual cable pair of wires to isolate the affected array section. The voltmeter reading (open circuit voltage) should be greater than 0.48 volt times the number of solar cells in series (listed under "Array Performance" on the front cover). To locate the defective module in the array section isolated above, follow the instructions in Step 2(b).

SYMPTOM

Array short circuit current low (from Test 3-1)

Checks and Repairs

1. Check for dirt buildup on any module or portion of a module. Clean according to Section 4.1.2.

2. Check for condensation, snow, or ice on module or any portion of a module. Wipe clean.

3. Check for shading of any module or portion of a module. Retest after removing obstruction.

4. Make sure array is aimed directly at the sun. Retest after correcting tilt.

5. Single frame arrays or when the problem is isolated to a single array frame (reference Step 6): Remove the attached junction box cover. Test each individual module for short circuit current as described in Test 3-1, Steps 3 and 4. Compare these values to the short circuit current values listed on the front cover under "Module Performance". Replace any module (reference Section 4.3) which fails Test 3-1. Make sure all connections in the junction box are tight and clean.

6. Multiframe Arrays: Perform Test 3-1 for each array section (cable) to determine the faulty section. Check for any loose terminals or broken wires within an external junction box. Also check all connectors, if any, for corrosion and tight mating of the male and female contacts. Clean or replace as necessary.

SYMPTOM

Excessive difference between array short circuit and battery charging current (from Test 3-1)

Checks and Repairs

1. Check for corrosion at the battery terminals. Clean terminals and cable leads. Retest.

2. If the array has a junction box(es) (either internal or external), remove the cover(s) and inspect for corrosion on all electrical connections within the box. Clean or replace damaged components. Retest.

3. Test each module individually as described in Steps 3, 4 and 6 of Test 3-1. Compare these values to the short circuit current values as listed on the front cover under "Module Performance". Replace any module(s) that fail Test 3-1 (reference Section 4.3).

4.3 MODULE AND DIODE REPLACEMENT

When it has been determined that a module or a blocking diode needs replacing, proceed as follows:

4.3.1 Replacement of Module

(a) Remove cover of junction box attached to array frame.

(b) Disconnect at the terminal strip the cable leads of the module being replaced.

(c) Loosen the threaded gland of the cable fitting through which the module cable enters the junction box. Pull the end of the cable out of the junction box.

(d) Remove the nuts and bolts holding the module onto the array frame. Lift off the module; save the hardware removed.

(e) Insertion of Replacement Module:
Reverse the removal procedure: (a) through (d) above.

4.3.2. Replacement of Blocking Diode Located in Junction Box

(a) Disconnect battery cable at battery terminals.

(b) Remove the junction box cover and the metal plate on which the terminal block is mounted. Loosen or remove cable leads from the terminal block, if necessary.

(c) The diode will usually be mounted on a heat sink. Make a sketch showing which lead goes to which terminal and how the hardware is assembled. Unsolder the leads to the diode. Remove the diode.

(d) Insert the new diode (exact same number as the diode being replaced). Take care to replace the hardware in the same order as was on the removed diode.

(e) Solder the leads to the new diode. Take care that the leads go to the same terminals as on the removed diode. (Array positive lead to anode; battery positive lead to cathode.)

(f) Replace the metal plate and the junction box cover.

(g) Reconnect the battery cable to the battery terminals.

4.3.3. Replacement of Blocking Diode Located in Module

A blocking diode within the module cannot be replaced in field. The module should be removed from the array frame (reference Section 4.3.1, a-d) and returned to Solar Power Corporation for repair.

5.0 TOOLS AND EQUIPMENT

5.1 INSTALLATION & MAINTENANCE TOOLS

Ratchet Handle (3/8" or 1/2" drive)
6" Extension
1/2" Socket and Wrench
9/16" Socket and Wrench
7/16" Socket and Wrench
3/4" Socket and Wrench
Screw Drivers (1/8" to 1/2" wide)
Slip Joint Pliers (1½" diameter grip)
Locking Pliers
Crimping Tool (VACO 22-10 or equivalent) and assorted crimp terminals
Wire Strippers
Diagonal Cutters (medium)
Compass (magnetic)
Inclinometer

5.2 TESTING EQUIPMENT

Simpson 260 VOM (or equivalent)
Immersion Thermometer
Battery Hydrometer

APPENDIX F

Battery Installation and Operating Instructions

C and D Battery Co.

Section 12-800
(Supersedes 12-600)

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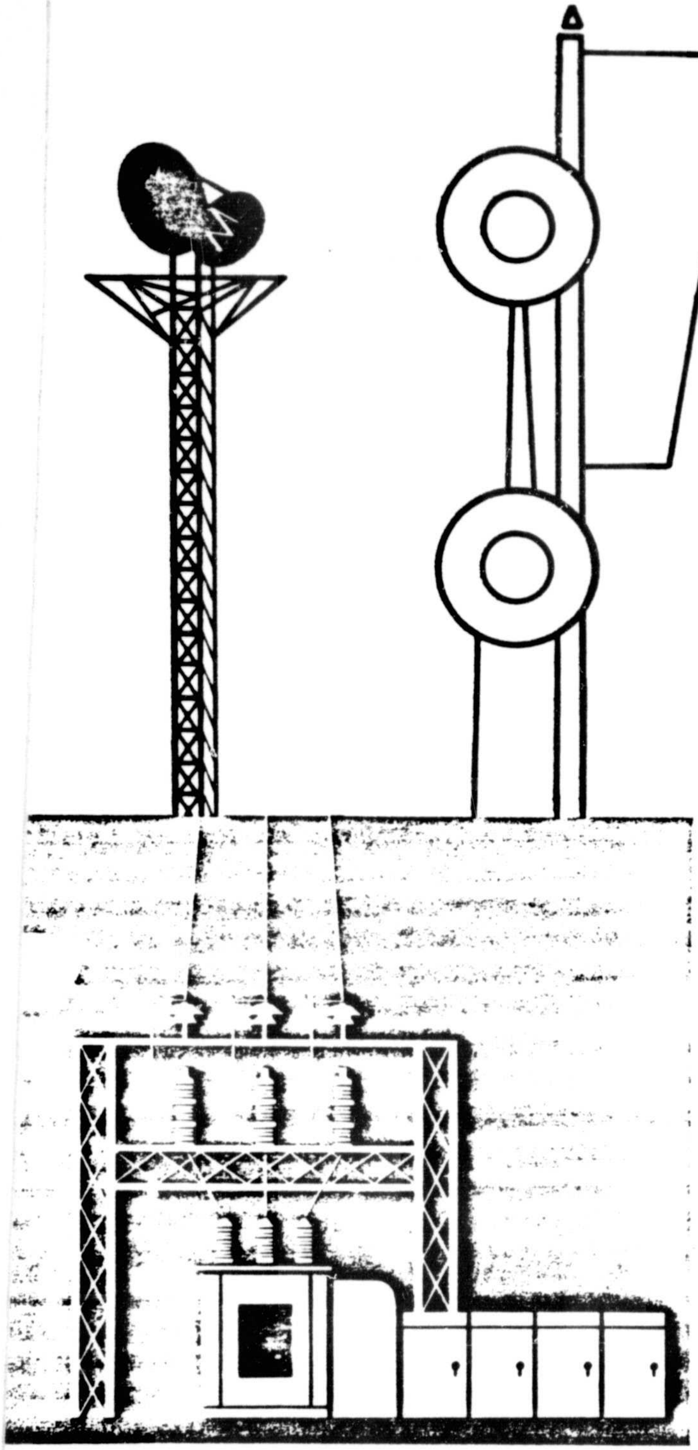
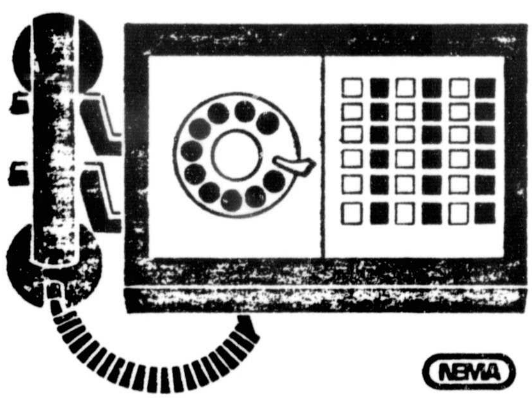


C&D

Installation and operating instructions for STATIONARY BATTERIES



C&D BATTERIES DIVISION

an Eltra company

TABLE OF CONTENTS

		PAGE
SAFETY RULES FOR MAINTAINING LEAD-ACID BATTERIES		inside front page
1.0 RECEIVING		1
1.1	Unpacking - Handling	1
2.0 STORAGE INSTRUCTIONS		1
2.1	Charged and Wet Batteries	1
2.2	Charged and Dry Batteries	1
3.0 INSTALLATION		1
3.1	Location	1
3.2	Racks	2
3.2.1	Standard Rack Assembly	2
3.2.2	Special Requirements - Standard Racks	2
3.2.3	Earthquake Protected (EP) Racks Assembly	3
3.2.4	Special Requirements - (EP) Racks	3
3.3	Arrangement of Cells	4
3.4	Preparing Contacting Surfaces	4
3.5	Coating Surfaces with NO-OX-ID Grease	4
3.6	Cell Interconnectors	4
3.7	Dual Intercell Connectors	5
3.8	Supplemental Instructions for Small Cells with Flag Terminals	5
3.9	Flame Arrestors	5
3.10	Numbering Cells	5
3.11	Suitable Water for Filling	6
3.12	Connecting Battery to Charger	6
4.0 INITIAL CHARGE		6
4.1	Constant Voltage Method	6
4.2	Recording Readings	7
5.0 OPERATION		7
5.1	Float Charging	7
5.2	Voltmeter Calibration	7
5.3	Equalizing Charge	7
5.4	Lead-antimony Batteries	8
5.5	Lead-calcium Batteries	8

		PAGE
5.6	After Emergency Discharge	8
5.7	Water Additions	8
5.8	Cleaning	8
5.9	Records	8
6.0 HYDROMETER READINGS - Specific Gravity		8
6.1	Hydrometer Readings	8
6.2	Pilot Cells	9
6.3	Specific Gravity	9
6.3.1	Loss on Float	9
6.3.2	Loss After Water Addition	9
6.3.3	Lag During Charge	9
6.3.4	Variation with Temperature	9
6.3.5	Variation with Electrolyte Level	9
6.3.6	Electrolyte Loss Correction	9
6.3.7	High Specific Gravity	10
6.3.8	Charge Indicators	10
7.0 GENERAL		10
7.1	Capacity and Testing	10
7.2	Low Cell Voltages	10
7.3	Temperature	11
7.4	Repairs	11
7.5	Tap Connections	11
7.6	Putting into Storage	11
8.0 INSTALLING TANK CELLS		11
8.1	Location	11
8.2	Installing Cells	11
8.3	Connecting Cells	12
8.4	Connecting Battery to Charger	12

1.0 RECEIVING

Every precaution has been used in packing the battery for shipment to assure its safe arrival. As soon as the battery is received, check the packing material for evidence of damage in transit. Spillage or leakage of electrolyte is indicated by wet acid stains. Broken or damaged boxes would be evidence of rough handling. If any of the above is observed, make a note of it on the bill of lading before signing.

1.1 UNPACKING - HANDLING

Cells or units are packed in individual cartons strapped to a wood pallet. Remove the straps and carefully open the cartons. Always lift cells from the bottom of the cell container; never by the cell posts. A lifting sling and spreader block may be provided and packed in the accessories box with cells of 400 ampere hours or over. Tilt the cell and slip the lifting sling under the cell, then install the spreader on top of the cell. Use the loops in the lifting sling for hoisting cell. (See Fig. 1)

At the first opportunity, check the electrolyte in each cell. It should be between the Hi and Lo level lines on the container. If the level is more than ½" below the top of the plates, order a new cell and file a claim for concealed damage against the carrier. If the plates are covered, but the level is lower than ½" below the high level mark, make no water additions until cells have been floating for one week, and contact factory or local C & D Representative. Fill the low level cell in question to the same level as the other cells in the battery. See Section 6.3.6.

2.0 STORAGE INSTRUCTIONS

2.1 CHARGED AND WET BATTERIES

2.1.2 Select an area for storage that is indoors, weatherproof, and preferably cool and dry. Do not allow the electrolyte to freeze because it will ruin the battery and can cause dangerous leaks. See Table V on page 12 for data on temperature vs. freezing point.

2.1.3 It is recommended that charged and wet storage batteries be placed in service before the date stamped on the shipping carton. If storage beyond this time is required, monitor battery at monthly intervals if possible to check specific gravity drop. When specific gravity drops 0.025 from nominal, the battery must be given a boost charge. Boost charge is conducted at equalize voltage.

2.1.4 Boost charges may be given to individual cells, groups of cells, or preferably, to the entire battery.

2.2 CHARGED AND DRY BATTERIES

2.2.1 As with wet batteries, storage should be in a ventilated, weatherproof, cool and dry building or enclosure.

2.2.2 Remove any packing container that indicates shipping damage may have resulted and inspect the thermoplastic jar for cracks or damage. **Do not remove the plastic vent seal until cells are to be filled with electrolyte to prevent foreign matter from entering and contaminating cells.**

2.2.3 Although it is recommended that dry batteries be stored no longer than 12 months from the date of shipment, it is recognized that longer periods may be required. Contact C & D Batteries Engineering Department, 3043 Walton Road, Plymouth Meeting, PA 19462.

2.2.4 Upon initial installation and filling, particular attention must be directed to "Activating Instructions for Dry-Charge Batteries", RS-564, if optimum performance and life are to be realized.

3.0 INSTALLATION

3.1 LOCATION

Whenever possible, install the battery in a clean, cool, dry place so that some cells are not affected by sources of radiant heat such as sunshine, heating units, radiators, or steam pipes. The battery is an electrochemical device and variations in temperature of more than 5°F will cause the cells to become unequal. See Section 7.3.

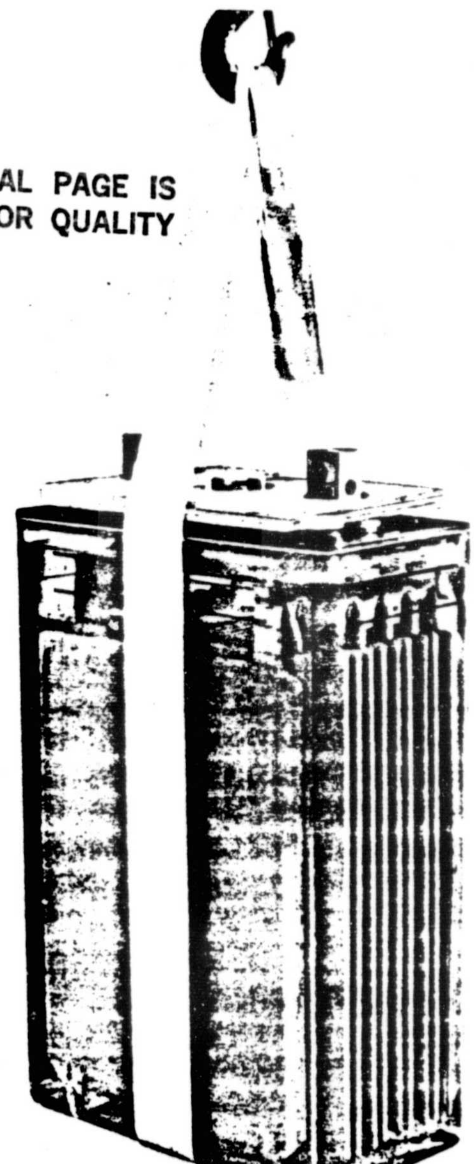


Figure 1

3.2 RACKS (See Fig. 5)

These may be from one to three tiers, or two or three steps arranged back to back, end to end, or individually. They are composed of steel angle supports and channel rails. Rail insulation is supplied. Assembly instructions and drawings are packed with the rack.

When locating the racks or rack sections, consider ease of cell accessibility so that individual cell readings and water additions may be made without difficulty.

CAUTION

- **When assembled, battery racks must be level and in conformance with the C&D drawing supplied with equipment to ensure that neither individual cells nor rack assembly can topple.**
- **Do not place battery cells on rack until rack is completely assembled and all bolts are tightened to specified torque (Steps 1-7 in Section 3.2.1) otherwise weight of cells may cause rack to shift and collapse.**
- **NEVER remove or loosen braces from a loaded battery rack. Removal of effective bracing can allow rack to shift and collapse.**

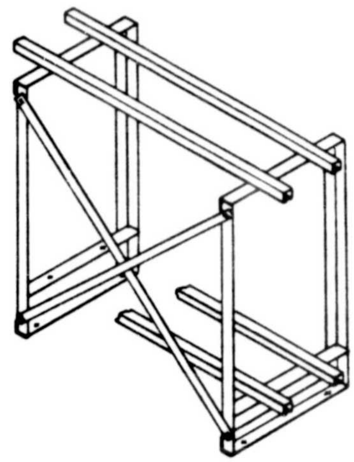
3.2.1 STANDARD RACK ASSEMBLY

1. Check received parts against Bill of Material on C & D drawing. **(DO NOT ASSEMBLE UNLESS ALL MATERIAL IS AT JOB SITE.)**
2. Mark frame location on floor and position frames.
3. Install braces onto frames as shown on drawing using the appropriate bolts, lock washers and nuts (Fig. 2). Hand tighten only.
4. Install rails when all the frames are in proper upright position in accordance with either Fig. 3, Style A or Fig. 3, Style B. Hand tighten only.
5. Check that frames are in correct position and the assembly is level in all directions, then tighten all nuts to a torque of 25 to 30 ft.-lbs. (Tighten braces first, then the rails and bolt frames to floor.)
6. Place rail cover onto rails, if not already installed when delivered. (Fig. 3)
7. Install cells, noting special requirements, space cells approximately ½" apart.

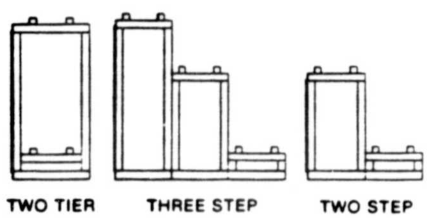
3.2.2 SPECIAL REQUIREMENTS — STANDARD RACKS

To provide sufficient stability, 2 and 3 tier racks **must be securely anchored to either the floor or wall.** For floor anchoring use two ½" bolts per each frame at the location of the pre-drilled holes. When wall mounting has been specified **use one ⅜" bolt for each mounting bracket supplied,** at position shown on the C & D drawing.

When the layout permits, racks of the same configuration shall be bolted back to back. This is accomplished by bolting together the frames at all of the points where braces are attached. Back to back installation will require the longer 1½" bolt supplied for this purpose. (Fig. 4)



TYPICAL STANDARD RACK ASSEMBLY



STANDARD RACK CONFIGURATIONS

Figure 5

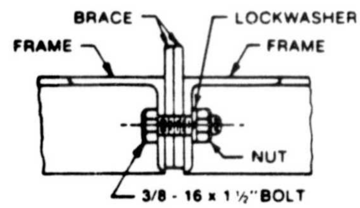


Figure 4

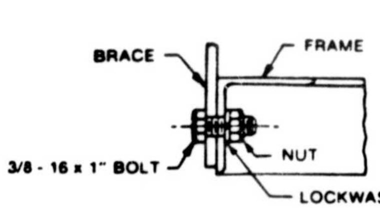


Figure 2

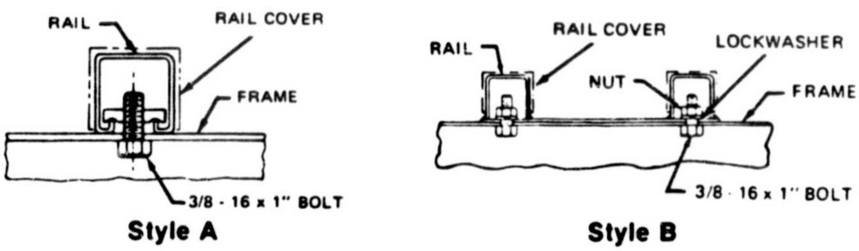


Figure 3

3.2.3 EARTHQUAKE PROTECTED (EP) RACKS ASSEMBLY (Fig. 6)

1. Check received parts against Bill of Material on C & D drawing. (**DO NOT ASSEMBLE UNLESS ALL MATERIAL IS AT JOB SITE.**)
2. Mark frame location on floor and position frames.
3. Install braces onto frames as shown on drawing using the appropriate bolts, lock washers and nuts (Fig. 2). Hand tighten only.
4. Install bottom rails and rear side rails (not the front side rails and end rails) when all frames are in proper upright position in accordance with either Fig. 3, Style A or Fig. 3, Style B. Hand tighten only.
5. Check that frames are in correct position and the assembly is level in all directions, then tighten all nuts to a torque of 25 to 30 ft.-lbs. (Tighten braces first, then the rails.)
6. Place plastic rail cover onto rails, if not already installed when delivered.
7. Install cells, noting special requirements, place the furnished plastic spacer between each cell (spacing ½" approx.)
8. Install front side rails, end rails and rail covers.
9. Install tie rods if required. Tightening of the tie rods shall not apply pressure of the side rails onto cells.

CAUTION

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- **When assembled, battery racks must be level and in conformance with the C & D drawing supplied with equipment.**
- **Do not place battery cells on rack until rack is assembled and bolts are tightened to specified torque. (Steps 1-6 in Section 3.2.3)**
- **NEVER remove or loosen braces from a loaded battery rack.**

3.2.4 SPECIAL REQUIREMENTS — E. P. RACKS

To provide sufficient stability, all racks must be securely anchored to either the floor or wall. For floor anchoring use two ½" bolts per each frame at the location of the pre-drilled holes. When wall mounting has been specified, use one ⅜" bolt for each mounting bracket supplied, at position shown on the C & D drawing.

When the layout permits, racks of the same configuration shall be bolted back to back. This is accomplished by bolting together the frames at all of the points where braces are attached. Back to back installation will require the longer 1½" bolt supplied for this procedure. (Fig. 4)

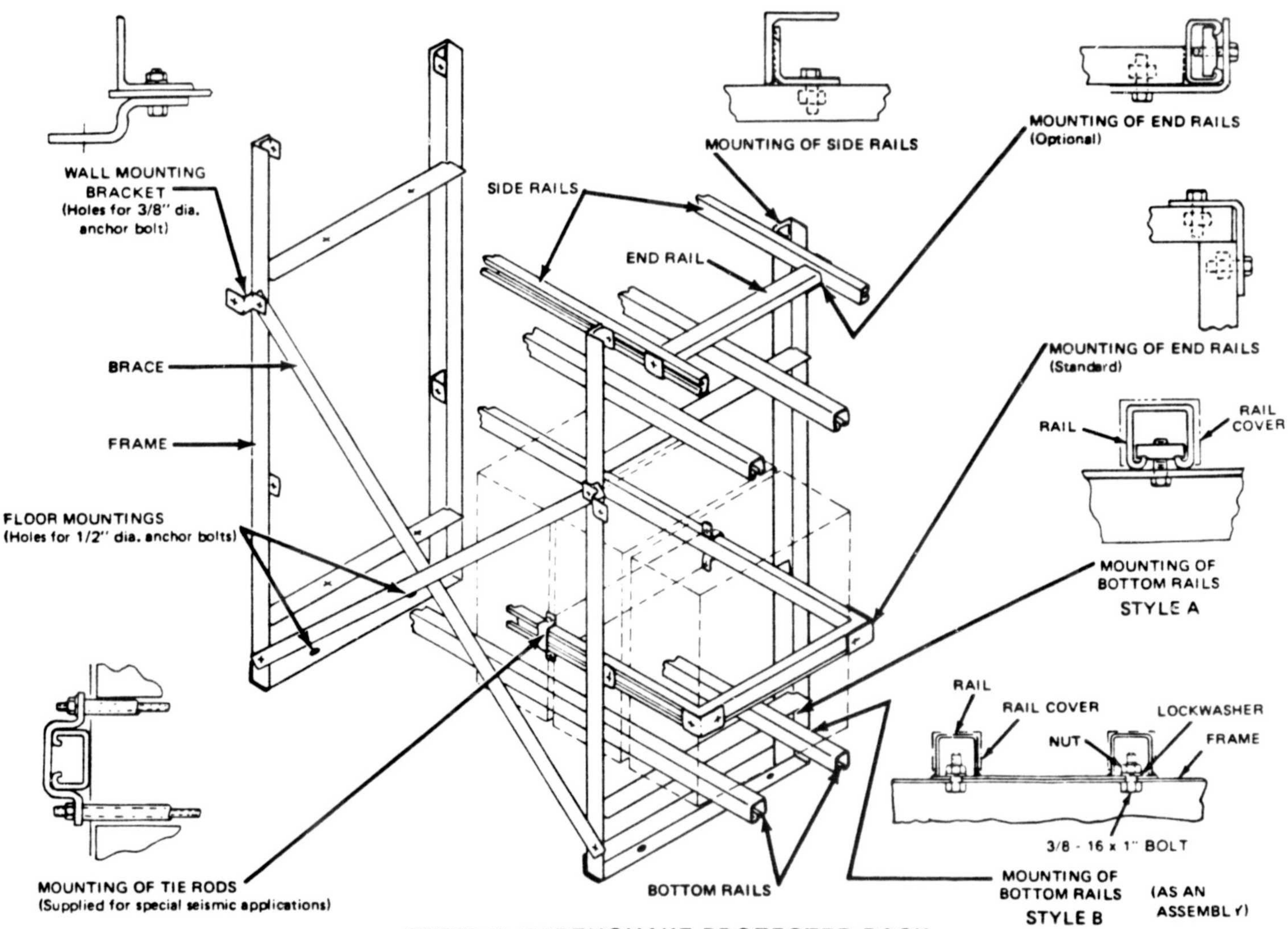

Figure 6 TYPICAL EARTHQUAKE PROTECTED RACK (2 TIER EP ILLUSTRATED)

3.3 ARRANGEMENT OF CELLS

Place the first cells on the bottom tier or step of the rack. Work from the center of the rack out to the two ends. Arrange the cells on the rack so that the positive post (terminal) of each cell can be connected to the negative post (terminal) of the next cell. Cell posts are marked with symbols molded onto the cover. A plus sign (+) denotes the positive post and a minus sign (-) denotes the negative terminal of the cell. When a rack drawing showing cell arrangement is supplied with battery be certain to arrange cells according to drawing so that cables may be properly connected to cells.

Cables connecting battery to charging equipment or bridging aisles are not supplied by C & D Batteries.

3.4 PREPARING CONTACTING SURFACES

All electrical contacting surfaces must have a clean and bright finish protected by NO-OX-ID grease before any connections are made.

Both sides of the intercell connectors should be inspected, particularly where they will contact a post. If any tarnishing or discoloration is noticed, it should be removed with the plastic bristle brush furnished in the accessory kit.

CAUTION: Do not use a wire brush, steel wool, or emery cloth to clean connectors because they will damage the lead plating.

Inspect both sides of each battery post which will contact an intercell connector. If discoloration or tarnishing is noticed, remove the NO-OX-ID grease if present with paper toweling. Clean the surface with either a wire or plastic bristle brush (See Table III for recommended type) until a clean and bright surface is obtained.

Note: Cells are normally supplied without NO-OX-ID grease applied to posts.

PRECAUTIONARY SAFETY MEASURES

1. **Always use protective insulating equipment such as insulated gloves and shoes and wear eye protection. Wrenches and tools should also be insulated.**
2. **Local, state and National Electric Code provisions should be observed at all times.**
3. **Always work with the battery ungrounded. Battery ground connections, if required, should be made last.**
4. **To avoid working with high voltages, break down battery into convenient lower voltage modules by skipping an interconnection every 60 cells or less.**

3.5 COATING SURFACES WITH NO-OX-ID GREASE

Heat the NO-OX-ID grease (included in the accessory kit) to a cream-like consistency with an electric hot plate or infrared lamp. Set the temperature to maintain this consistency.

CAUTION: If the hot plate lacks a thermostat, exercise extreme care to avoid overheating the grease. Do not use heaters with open flames.

Apply a light coat of NO-OX-ID grease to ends of connectors by dipping them into the melted grease coating approximately two inches up from each end. (SEE Figure 7) On 4 and 6 hole connectors, use the one inch paint brush supplied to apply the melted grease to both sides of the middle holes and contact areas.

Wipe all post surfaces with a clean cloth or paper toweling to remove any brush residue and apply a thin film of NO-OX-ID grease to all post surfaces. This inhibits oxidation. Wipe all grease from the cell covers.

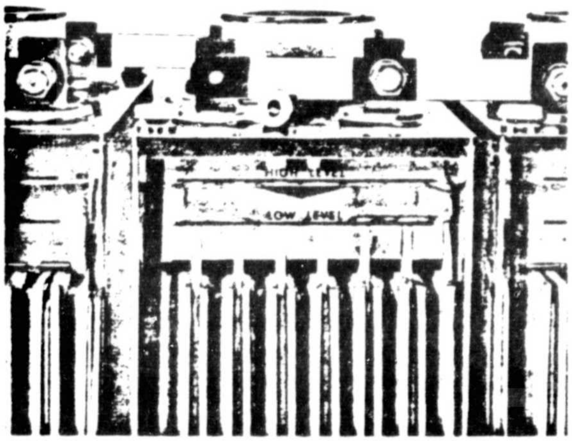

Figure 7

3.6 CELL INTERCONNECTIONS

Place intercell connectors against cell posts and insert brass stud or stainless steel bolt, as supplied, in the hole in the post. Put heavy duty washers in place and screw on nut when stainless steel bolts are supplied. In the cases where one brass stud and two lead nuts are supplied, make certain that an equal number of threads are engaged on each nut.

Tighten connections using two wrenches, one of them being a torque wrench. Initially, set torque 5 inch-pounds below the recommended value shown in Table III.

Note: Torque wrenches not supplied by C & D Batteries.

After the cells within the modules have been interconnected, recheck the torque of all connections in sequence and adjust the torque to the recommended value.

Contact areas of interconnecting cables, terminal connectors, lugs, etc. should also be cleaned with the plastic bristle brush, coated with a thin film of NO-OX-ID grease and the bolts tightened using the same procedure outlined above.

Connect modules following the same procedure. Immediately check the total voltage of the cells in the battery with a DC voltmeter. The reading should be approximately 2.05 volts times the number of cells in the battery. If the reading is less than this value, one or more of the cells are installed backwards, or the voltmeter is incorrect. Recheck the polarities of all cells.

CAUTION: All connections should be checked at regular intervals (such as every six months) to insure that the connections are clean and tight. Never operate a battery with loose or corroded connections. When checking connections, disconnect the battery from the load and the charging equipment and follow all the precautionary measures outlined above.

3.7 DUAL INTERCELL CONNECTORS

Certain large size cells for high rate discharge batteries are supplied with auxiliary interconnectors. These connectors physically parallel the two intercell connectors normally connecting the outside posts of one cell with those of its neighboring cells. The auxiliary intercell connectors are shorter in length than the normal connectors and increase the connector thickness between cells. Double intercell connectors are held in place with stainless steel bolts and hardware in which the bolts are longer to accommodate the added thickness of two extra intercell connectors. A special installation drawing for cell arrangement will normally be supplied by C & D Batteries which details the connection methods and layout.

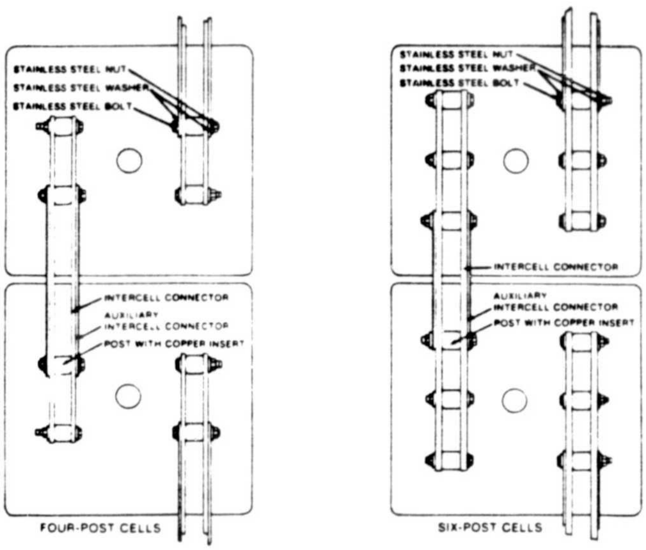

Figure 8

3.8 SUPPLEMENTAL INSTRUCTIONS FOR SMALL CELLS WITH FLAG TERMINALS

Small cells with flag terminals require a special assembly procedure because too much torque against the flag terminal can snap it off or cause damage to the ductile components inside the battery.

Arrangement of cells, preparation of contacting surfaces and coating the contacting surfaces with NO-OX-ID grease is basically as that described for larger batteries (See Sections 3.3, 3.4, and 3.5). The only difference is that extra care must be taken in the final tightening of the intercell connections. For small batteries, these connectors are normally either a "Z" shaped strap or a short cable with a lug at either end.

After the batteries are arranged on the rack and the contacting surfaces cleaned and coated with a film of grease, the intercell connectors should be put in place and the lead nut and bolt assemblies tightened finger tight.

Final tightening of the nut and bolt assemblies is accomplished with two wrenches (See Figure 9). An open end wrench is coupled with the square section of the bolt to provide a counter-torque when the nut is tightened. A hexagonal wrench is then coupled with the lead casted nut and the assembly tightened to the torque value shown in Table III. A small torque wrench may be utilized in place of the hexagonal wrench for more accurate setting of torque.
Note: Torque wrenches not supplied by C & D Batteries.

CAUTION: It is of utmost importance that two insulated wrenches be used in counter-torque to avoid excessive stress to the flag terminal and post assembly.

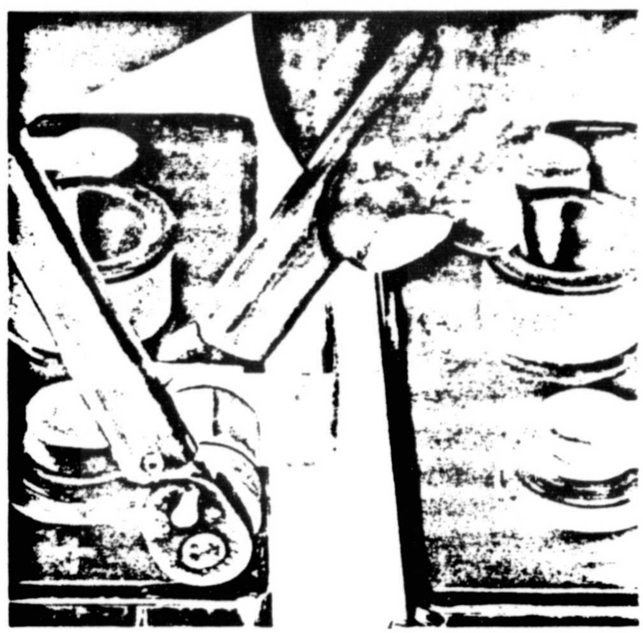

Figure 9

3.9 FLAME ARRESTORS

Larger cells and batteries are shipped with orange colored vent plugs. Remove and discard these vent plugs and install the flame arrestors.

3.10 NUMBERING CELLS

Plastic cell numbers are provided in the accessory kit for larger cells. Customary practice is to start with "1" at the positive terminal and to follow the electrical circuit with succeeding numbers. To install, first mark the location of the numbers on the jars with chalk. Remove the backing on the number and press it firmly into position. Do not scratch the plastic jar.

3.11 SUITABLE WATER FOR FILLING

If in doubt about the suitability of the local water supply for use in lead-acid batteries, consult your nearest C & D Representative. If he does not have a recent analysis report available, send a one-quart sample in a chemically clean non-metallic container and stopper, prepaid to Technical Services Dept.,C & D Batteries Division, Eltra Corporation, 3043 Walton Road, Plymouth Meeting, PA 19462. The sample will be analyzed and a report as to its safety for use in lead-acid batteries will be forwarded. Indicate the source of the water and the sender's name and location on the sample.

The quantity of water consumed by a battery is proportional to the amount of charge is receives. Lead-antimony batteries begin their life with low water consumption, which increases as much as five or more times toward the end of their life. Lead-calcium batteries, because of the greater purity of their components, require only about one-tenth the water needed by equivalent-sized new lead-antimony batteries. This low requirement remains constant during their entire life. Fig. 10 gives the approximate water consumption for various size cells at the normal operating temperature of 77°F.

3.12 CONNECTING BATTERY TO CHARGER

Only direct current (dc) is used for charging. With the charging source de-energized, connect the **positive** terminal of the battery **to** the **positive** of the charger or system and the **negative** terminal of the battery **to** the **negative** of the charger or system. Re-energize the system following procedures that are provided in charger manual.

4.0 INITIAL CHARGE

All batteries shipped wet and fully charged lose some charge in transit or while standing idle before installation. At the first opportunity, they should be given their first or initial charge using the following method.

4.1 CONSTANT VOLTAGE METHOD

This method of giving the initial charge is the most common and is used when circuit voltage limitations make it impractical to use the constant current method. First, determine the maximum allowable voltage that may be applied to the connected equipment. Divide this voltage by the number of cells in the battery, thus obtaining the maximum voltage per cell. Determine if the battery is a lead-antimony or lead-calcium type by the nomenclature on the cell. If **lead-antimony**, refer to the following table and charge for the time indicated at the maximum voltage permitted by the associated equipment.

TABLE I - LEAD-ANTIMONY CELLS

CHARGE VOLTAGE PER CELL (VPC) (1.210 SPECIFIC GRAVITY)			
INITIAL		FLOAT	EQUALIZE
VPC	HOURS	VPC	VPC
2.39	40	2.15 to 2.17	2.33 for 8 to 24 hrs.
2.36	60		
2.33	110		
2.30	168		
2.24	210		

If **lead-calcium** the following applies:

TABLE II - LEAD-CALCIUM CELLS

CHARGE VOLTAGE PER CELL (VPC)				
SP. GR. OF CELLS	FLOAT VPC		INITIAL/EQUALIZE (VPC)	
	MIN.	NOMINAL	CRITICAL CELL VOLT.	NOM. VPC
1.210	2.17	2.20-2.25	2.13	2.33-2.38
1.225	2.18	2.22-2.27	2.15	2.36-2.40
1.250	2.20	2.25-2.30	2.18	2.38-2.43
1.275	2.23	2.29-2.34	2.20	2.40-2.46
1.300	2.27	2.33-2.38	2.23	2.45-2.50

TABLE III - BRUSHING & TORQUE SPECIFICATIONS FOR CELL CONNECTIONS

CELL TYPE	RECOM. TORQUE	TYPE BRUSH
Cells with posts that do not have copper inserts:		
Communications Batteries KT, KCT, LT, LCT; UPS & Switchgear Batteries DU & DCU 13, 15, 17; KA & KC 5, 7, 11, 13; KY & KCY-7; KCX 7, 9, 11, 13, 15, 17; LA & LC - 13, 15, 17; LY & LCY - 5, 7; Photovoltaic Batteries DCPSA - 11, 13, 15, 17; DCPSD - 9, 11, 13; KCPSA - 5, 7, 9, 11, 13, 15, 17; KCPSD - 5, 7, 9, 11, 13; LCPSA - 5, 7, 11, 13, 15, 17, 19, 21, 23, 25; LCPSD - 5, 11, 13, 15, 17, 19	110 inch-lbs. -0 inch-lbs. +10 inch-lbs.	wire brush
Mini-Tank Cells MT & MCT	160 inch-lbs. -0 inch-lbs. +10 inch-lbs.	wire brush
Cells with posts that have copper inserts:		
Tank Cells RHA & RHC; UPS & Switchgear Batteries KA & KC-15, 17, 19, 21; KY & KCY-23, 25; KCX-19, 21, 23, 25, 27, 29, 31, 33; LA & LC - 19, 21, 23, 25, 27, 29, 31, 33; LCX - All sizes; LY & LCY - 9, 11, 35, 37, 39	160 inch-lbs. -0 inch-lbs. +5 inch-lbs.	plastic bristle brush
Cells with large flag terminals (no inserts):		
DU & DCU - 3, 5, 7, 9, 11; DCPSA - 3, 5, 7, 9; DCPSD - 3, 5, 7	70 inch-lbs. -0 inch-lbs. +5 inch-lbs.	wire brush
Cells with small flag terminals (no inserts):		
A, AC, B, BC and small specialty batteries	15 inch-lbs. -3 inch-lbs. +0 inch-lbs.	wire brush

Lead-calcium batteries, supplied wet and fully charged, will automatically receive their freshening and equalizing charges when normal float voltages at corresponding specific gravities are maintained if charged within 6 months from time of shipment from factory. If longer than 6 months it will be necessary to charge at equalize voltage.

Limits are determined and charge terminated when the lowest voltage cell in the battery is less than 0.05V below the average cell voltage which usually stabilizes during an observed 24 hour period.

4.2 RECORDING READINGS

At the completion of the initial charge, record voltages and specific gravities of individual cells while still on charge and keep for future reference. Specific gravities (corrected to 77°F. electrolyte temperature) should be between 1.200 and 1.220 for the nominal 1.210 specific gravity battery, 1.240 to 1.260 for the nominal 1.250 specific gravity battery, and 1.290 to 1.310 for the nominal 1.300 specific gravity battery, with the electrolyte at the full mark (See Figure 8).

Caution: Potentially explosive gases.

All storage batteries give off some potentially explosive gases when charging. Cells equipped with flame arrestors are protected from internal explosions, but caution should still be used not to bring open flame or sparks near the battery.

5.0 OPERATION

5.1 FLOAT CHARGING

Most stationary batteries are continuously connected to control circuits which must be energized at all times. This is accomplished by connecting the battery in parallel with a continuously operating charger and the desired load circuits. The charger is then adjusted to a voltage which will enable the battery to obtain just enough current to keep it fully charged. Under certain conditions, such as with lead-antimony batteries and lead-calcium batteries that are floated below recommended voltage, periodic equalizing charges may be necessary. The charger also furnishes current for the connected load. This is called floating operation. It assures a fully charged battery for any emergency service.

5.2 VOLTMETER CALIBRATION

Panel voltmeters used for float charging circuits should be kept in accurate calibration by checking with a known standard at least every twelve months. (See Tables I and II for float voltages).

5.3 EQUALIZING CHARGE

This is a charge given at a higher voltage than the floating charge for a definite number of hours depending upon the value of the charge voltage. Its purpose is to compensate for any irregularities that may have occurred, such as low floating voltage for a prolonged pe-

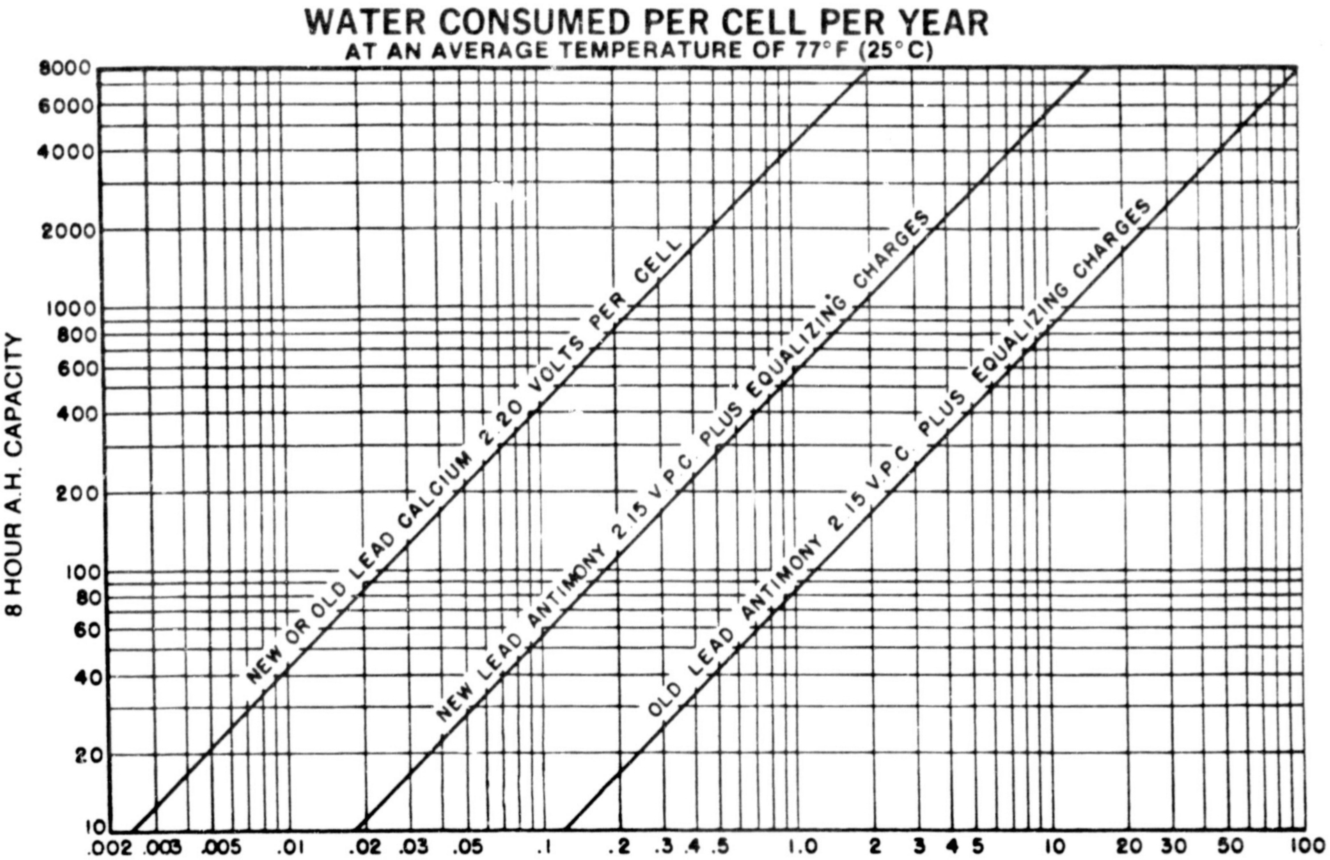

Figure 10

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riod of time due to faulty adjustment of the charger, or to a panel voltmeter which is improperly calibrated on the high side or to compensate for the differences between individual cells in a string. It is also useful in restoring the battery to full charge in a minimum time after an emergency discharge. (See Tables I and II for equalize voltages)

5.4 LEAD-ANTIMONY BATTERIES

Lead-antimony batteries require an equalizing charge about every one to three months using the same procedure as in initial charging.

5.5 LEAD-CALCIUM BATTERIES

Usually lead-calcium batteries do not need equalizing charges when floated at the recommended voltage as indicated in Table II. However, lead-calcium batteries which operate at the minimum float value should be given an equalizing charge whenever the lowest cell in the string drops more than 0.04 volts below minimum float voltage or to the critical voltage in Table II.

5.6 AFTER EMERGENCY DISCHARGE

Both lead-antimony and lead-calcium batteries should be recharged as quickly as possible following an emergency discharge. Where conditions permit, this can be done by raising the bus voltage to the maximum allowed by the other circuit components but not to exceed the values listed in Tables I and II.

5.7 WATER ADDITIONS

In addition to normal evaporation, as batteries are floated and charged, a small quantity of the water in the electrolyte is broken down into hydrogen and oxygen by the charging current. These gases are dissipated through the flame arrestor. As this takes place, the electrolyte level gradually drops so that from time to time it is necessary to replace this loss with water. Keep the electrolyte level between the high and low level lines by adding approved or distilled water as required (See Section 3.11).

5.8 CLEANING

Wipe the outside of the cells as necessary with a water-moistened cloth to remove dust and ordinary dirt. If electrolyte is spilled on the covers, neutralize it with a cloth moistened with a solution of baking soda and water mixed in the proportion of one pound of soda to one gallon of water. When fizzing stops as fresh soda solution is applied, wipe with a water-moistened cloth to remove all traces of soda.

Never use any solvents, detergents or other cleaning compounds or oils, waxes or polishes on the plastic containers or covers since such materials may attack the plastic and cause it to craze or crack. Always keep the connectors and posts corrosion-free and coated with NO-OX-ID grease. The covers and containers should be clean and dry at all times.

C & D is presently supplying some stationary batteries encased in clear polycarbonate plastic containers which can be identified by their appearance. (Their color is generally water-white, although when viewed from an angle they have a bluish tint.) They are extremely acid resistant, free from internal stresses and have superior impact resistance.

CAUTION - CLEANING POLYCARBONATE JARS

- **Clean or wash the polycarbonate containers with clear water only.**
- **Neutralize acid spills with a solution of sodium bicarbonate (baking soda). NEVER use ammonia, soda ash, sodium hydroxide or any strong alkalies. If alkalies are inadvertently spilled on the containers, they should be immediately washed off with water.**

5.9 RECORDS

A record of the battery operation is invaluable (See Fig. 13 as sample) in helping to determine causes for associated equipment difficulties; for checking on maintenance procedures; and for indicating remedial action when necessary. At periodic intervals, which will necessarily vary with location and system routines, the following information should be recorded and reported to the supervising authority: date; date and description of last equalizing charge (if lead-antimony); battery floating voltage; pilot cell hydrometer reading; pilot cell temperature; and quantity of water added.

Periodically, read and record individual cell specific gravities and voltages and note any unusual conditions.

If irregularities occur, consult the nearest C & D Representative; or send a copy of the latest report c/o Technical Services Department, Stationary Batteries, C & D Batteries Division, Eltra Corporation, 3043 Walton Road, Plymouth Meeting, PA 19462 for analysis and recommendations.

6.0 HYDROMETER READINGS SPECIFIC GRAVITY

Specific gravity is a measure of the strength or weight of the acid in the electrolyte using water with a specific gravity of 1.000 as a base; for example, 1.210 specific gravity means that the electrolyte is 1.210 times heavier than the corresponding volume of water.

6.1 HYDROMETER READINGS

A hydrometer float inserted in a glass barrel rubber bulb syringe is used to measure the specific gravity of the electrolyte. The float is graduated in points of specific gravity, 0.001 equals one point. The gravity is read on the hydrometer scale at the level at which it floats in the electrolyte (See Fig. 11).

When taking hydrometer readings, always hold the hydrometer syringe vertically and make sure the float is floating freely with no pressure on the bulb.

The glass parts of the hydrometer syringe should be washed as needed with warm water and soap and rinsed with clear water in order to keep them clean, accurate, and to simplify readings.

The fully charged specific gravity is as specified in the particular battery and is shown on the nameplate. As the battery discharges, the hydrometer will float lower because the specific gravity decreases. When recharged, the specific gravity will return to its original value. A hydrometer reading is therefore an indication of the charged or discharged condition of the cell. However, the gravity readings on recharge lags behind the energy

input and does not indicate true charged condition. Mixing of the electrolyte is dependent upon the amount of gas generated and natural diffusion. Usually specific gravity measured at the top is only representative following an equalizing charge.

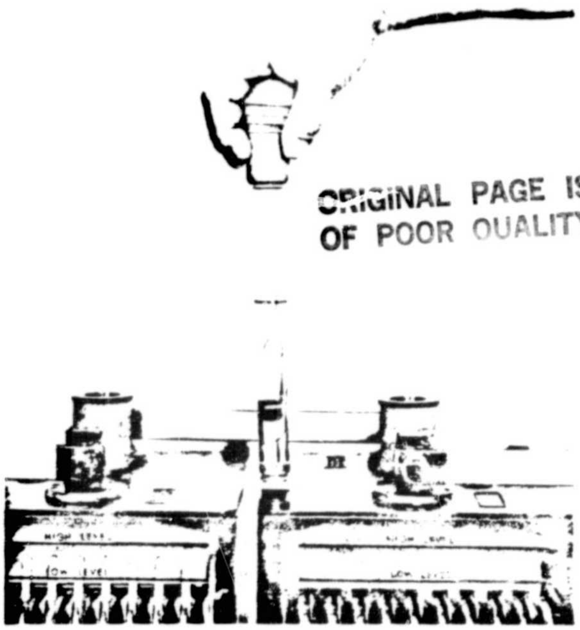

Figure 11

K and L size cells have two hydrometer reading tubes built into diagonal corners of the cover on single cells, and at the front of the four-cell units. They are covered with white plastic caps.

Their purpose is to enable the readings of the electrolyte specific gravity to be taken with a long nozzle hydrometer syringe, at a point about one-third down from the top of the plates. In order to obtain an accurate reading of specific gravity it is necessary to sample the electrolyte from the gravity sampling tubes discharging the first hydrometer sample into the filler vent and withdraw another sample for the reading. Discharge the second sample into the filler vent to avoid spillage of acid.

6.2 PILOT CELLS

One cell in a battery is usually selected as a pilot cell for recording readings. Since all cells in the battery receive the same amount of charge or discharge current their specific gravities will fall or rise together.

Because a slight amount of electrolyte is lost in taking a hydrometer reading, change to a different pilot cell after about thirty readings. This distributes the electrolyte loss over all the cells in the battery rather than concentrating it to one cell. Always return the electrolyte in the hydrometer syringe to the cell from which it came.

6.3 SPECIFIC GRAVITY

6.3.1 LOSS ON FLOAT

A gradual lowering in the specific gravity of the pilot cell from day to day or week to week would be an indication of insufficient charge caused by low floating. Ordinarily, when floating charge is correct, the hydrometer reading will stay close to the maximum value for the cell.

6.3.2 LOSS AFTER WATER ADDITION

When water is added to a cell, it does not mix immediately with the electrolyte so that a hydrometer reading taken at this time will not indicate the true specific gravity. The mixing or diffusion time is usually several days for antimony cells and several weeks for calcium cells in floating service. These times vary with the quantity of water added.

6.3.3 LAG DURING CHARGE

When the battery is discharged, the specific gravity drops uniformly during the discharge period. However, on the subsequent recharge, it always lags behind the true specific gravity of the cell restored on charge. This is because during charge, strong acid is released from the plates and falls toward the bottom of the cell from where it gradually diffuses through the solution.

6.3.4 VARIATION WITH TEMPERATURE

The actual volume of electrolyte in a cell changes with the temperature which causes a change in the observed hydrometer reading. The normal or standard cell temperature is 77° F. or 25° C. If the electrolyte temperature is above this point, the observed hydrometer reading may be corrected to 77° F. by adding one point (.001) for each three degrees above 77° F.

Conversely, if the electrolyte temperature is below 77° F., the hydrometer reading may be corrected to 77° F, by subtracting one point (.001) for each three degrees that the temperature is below 77° F.

6.3.5 VARIATION WITH ELECTROLYTE LEVEL

The specific gravity reading of a cell is also affected by the electrolyte level. If the electrolyte level is at the full mark and its specific gravity is 1.210, it will read approximately 15 points (.015) higher, or 1.225, when the level is lowered approximately ½ inch. As a result of the conditions outlined in Section, 5.7, the electrolyte becomes more concentrated. The following table illustrates how a hydrometer reading of the electrolyte will vary at different temperatures and for different levels in the same fully charged cell.

Electrolyte Temperatures

Electrolyte Level	62° F.	77° F.	92° F.
Full	1.215	*1.210	1.205
½" Low	1.230	1.225	1.220
1" Low	1.245	1.240	1.235

*Normal

6.3.6 ELECTROLYTE LOSS CORRECTION

The fully charged specific gravity gradually drops over a period of years at the rate of about one point (.001) per year due to a slight loss of electrolyte from spillage when taking hydrometer readings. This loss is not harmful and need not be corrected. However, it sometimes happens that one or more cells may lose an appreciable amount of electrolyte because of leakage, overwatering or spillage in handling. **Particularly if plates are exposed,** this loss should be promptly corrected! If available, use acid with the same specific gravity as that specified on nameplate on top of cell.

If not, remove a small quantity from each of the other cells in the battery and add this to the low level cell so that plates of this cell may be covered. If of sufficient magnitude (more than ⅛" per cell) then this loss must be replaced by obtaining the proper specific gravity electrolyte and adding the correct quantity to each of the cells.

Low fully charged specific gravity may also be corrected by the addition of 1.210 electrolyte to the low cells instead of water when the levels have dropped as indicated in the table. For example, assume that one cell in a battery reads 1.190 with full level corrected to 77°F. The other cells read normally at 1.200 - 1.220. The one cell is low because of electrolyte loss which was originally, but erroneously, replaced with water. Its voltage on float and equalizing charge is about the average of the battery. When the electrolyte level has dropped to ½" below the full mark due to evaporation and dissociation, the gravity of this cell will have increased to 1.205. It only remains then to fill this one cell to the full mark with 1.210 or 1.215 electrolyte in order to restore it to normal specific gravity. The other cells would, of course, be filled with water. This same procedure may be applied to cells which have nominal specific gravity other than the 1.210 sp. gr. indicated above.

Electrolyte should never be added to a cell unless some has been lost or until it is proven by prolonged charging, such as the initial charge, that all electrolyte is out of the plates and that the cell voltage on charge is normal. The unwise addition of electrolyte is a serious form of abuse and can result in permanent damage.

6.3.7 HIGH SPECIFIC GRAVITY

High fully charged specific gravity seldom occurs, but if found to be above normal nameplate rating it may be adjusted downward by removing electrolyte and replacing it with water. For example, assume that one cell reads 1.235 specific gravity with electrolyte at high level and corrected to 77°F. instead of 1.210. If ½" of electrolyte is removed from the cell, and replaced with water, the resultant specific gravity will be 15 points lower or 1.220, which will bring it within normal limits.

6.3.8 CHARGE INDICATORS

Some C & D Batteries are equipped with an assembly of up to three colored balls which float within a cage in the electrolyte. They are designed to float at different specific gravities depending upon the charged condition of the cell. At full electrolyte level, they indicate the following:

ALL FLOATING	FULLY CHARGED
GREEN DOWN	1/10th DISCHARGED
WHITE DOWN	1/3 DISCHARGED
RED DOWN	2/3 DISCHARGED

7.0 GENERAL

7.1 CAPACITY AND TESTING

Batteries are rated on an ampere-hour basis or their ability to deliver a certain number of amperes to the load for a specified amount of time before the cell voltages drop to a given potential. It is important to recognize a battery or cell produces a different ampere-hour capacity with respect to the rate at which cell is discharged. Consult the individual specification sheets published by C & D Batteries for various cell types. C & D lead-acid batteries and cells are designed for optimum discharge characteristics or specifically high-rate or long low-rate discharge requirements as reflected in the 3 hour and 8 hour rates published in the specification sheets. The 3 hour maximum discharge is typically utilized in applications where 10 - 15 minute discharge times are normally encountered. Short high-rate discharges frequently permit batteries to discharge to lower end potentials such as 1.70 to 1.67 volts per cell. These potentials are not practical end potentials for long low-rate discharges which normally terminate at 1.75 volts per cell or higher.

Low battery temperature must be considered when estimating battery size. Figure 13 on page 12 shows the effect of temperature on ampere capacity at various discharge rates.

Capacity tests on lead-acid batteries are beyond the scope of this booklet but are discussed in detail in the IEEE STD 450 and other Professional Society standards. It is, however, important to recognize that stationary batteries/cells are designed for emergency standby operation and excessive testing or cycling of a battery can materially shorten its life. Repetitious testing occasionally occurs on initial installation and qualification testing. Normal qualification tests as discussed in the IEEE Standard are not harmful to the life of a battery but repeated testing which discharges and recharges a battery many times in a relatively short period of time materially affects the long life typical of the original design of stationary batteries. C & D Batteries can supply batteries specifically designed for cyclic service. Consult the C & D factory and/or C & D Representative concerning initial testing procedures and special service requirements.

7.2 LOW CELL VOLTAGES

With proper floating operation at the recommended voltages and with individual cell temperatures varying not more than 5°F, cell voltages should be within plus or minus .02 volts for lead-antimony and plus or minus .04 volts for lead-calcium batteries. Under such conditions, the fully charged specific gravity, corrected for level and temperature, will be close to nameplate rating.

When individual cells read lower than normal, it is logical to conclude that for some reason/s the charging has not been sufficient. Some causes could be as follows:

1. *Panel voltmeter reading high.* This results in a low float voltage. Recalibrate the panel voltmeter.
2. *Poor intercell or terminal connections.* Remove connections, clean contact surfaces, neutralize with soda solution, dry, coat with NO-OX-ID grease and reassemble. Refer to Section 3.4, 3.5 and 3.6.

3. *Large frequent variations in the connected load which the charger is unable to supply.* This results in small successive battery discharges and acts similar to a low average floating voltage. To offset this condition increase the charge voltage about 0.02 volts/cell. Check after a month or so and if still low raise float voltage another 0.02 volts/cell if connected load can withstand the higher float value. If supply voltage cannot be increased to the new level, more frequent equalizing charges will be necessary.
4. *A temperature variation between cells of more than 5°F.* The warmer cells drop to a lower voltage because they require more floating current to keep them fully charged. Shield the warm cells from the external heat source affecting them.
5. *Impurities in electrolyte inadvertently introduced into the cell such as a metallic object, etc.* This foreign material is dissolved in the electrolyte resulting in a contaminant which increases the rate of internal loss. Unless the amount of contaminant is very small, the affected cell or cells will have to be replaced.

7.3 TEMPERATURE

The battery is essentially an electrochemical device. Heat enhances chemical activity; cold slows it down. Normal battery operating temperatures are between 60 and 90°F. averaging about 75°F. Higher than normal temperature has the following effects on the battery:

1. Increases capacity.
2. Increases internal discharge or local action losses.
3. Lowers cell voltage for a given charge current.
4. Raises charging current for a given charge voltage.
5. Shortens life.

Lower than normal temperatures have the opposite effects. In general, a battery in a cool location will last longer and require less maintenance than one in a warm location.

7.4 REPAIRS

In case of accidental damage to the containers or covers of one or more cells after a battery has been installed, consult the C & D Technical Services Dept.

7.5 TAP CONNECTIONS

Tap connections will unbalance the battery. Therefore taps for electrical connections should never be used. This would result either in partial or complete discharge of the group of cells which are furnishing current to the additional load, or result in overcharging of the untapped cells.

If a lower battery voltage for some circuit is necessary, a separate battery and charger should be provided. If a tap is unavoidable, furnish complete details to C & D Batteries who will be glad to recommend the most economical and satisfactory solution to the problem.

7.6 PUTTING INTO STORAGE

A floated battery yields the maximum life and therefore should not be stored on open circuit unless it is unavoidable. If storing on open circuit is unavoidable, then prior to de-energizing:

1. Fill the cells with water to the high level.
2. Allow time for mixing of water and electrolyte.
3. De-energize after battery is fully charged.
4. Disconnect the battery terminals or remove any battery fuses, so that there is no discharge through the circuit. Then as an added precaution, open one intercell or interunit connector on each row of batteries. Store battery at approximately 77°F. (25°C) or lower if practical.

Monitor battery at monthly intervals, if possible, to check specific gravity drop. When specific gravity drops 25 points the battery must be given a boost charge. To protect battery it should be placed on charge every three months if lead-antimony and every six months if lead-calcium. A dry-charged battery must be activated within one year (see pages 14, 15 and Section 2.2.3).

When returning the battery to service, remake all open connections, replace fuses and treat as a new battery by giving an initial charge.

8.0 INSTALLING TANK CELLS

8.1 LOCATION

The cells should be placed on a previously leveled area of sufficient size to accept the cells in an orderly configuration.

Since there is a ±¼ inch tolerance in jar height, it is a good practice to measure the cell height when selecting cells for placement. Install the tallest jars first and place the shortest jars at the opposite end of the group.

8.2 INSTALLING CELLS

CAUTION: Do not lift the cell by the terminal posts. Use the illustrated cell lifter shown in Figure 12 (C & D Part No. PH-773 - Dwg. M-3461) which may be borrowed from C & D. Raise the lifter until the insulated surface on the under side of the cross m[illegible]rs clears the

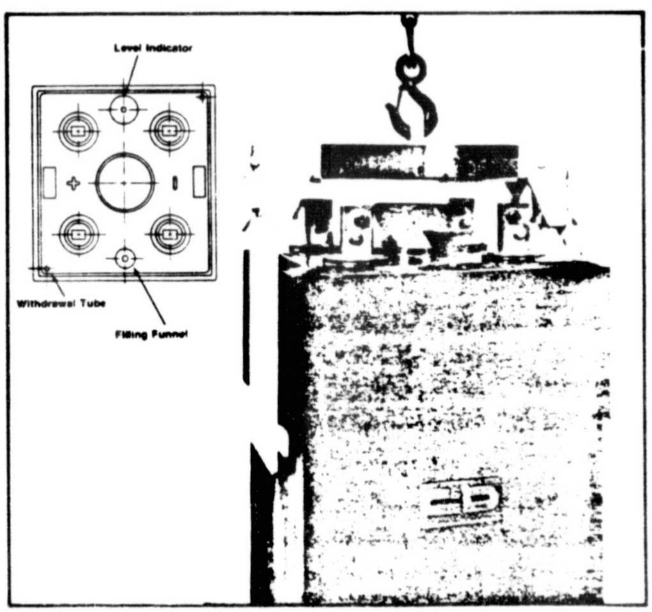

Figure 12

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terminal posts of the cell. Center the lifter above the cell. Draw the side plates of the cell lifter against cell with the aid of the adjusting wing nut screw. The side plates should be adjusted equally.

Raise the lifter until the lifting bar edges enter the slots on the sides of the cell. These slots are at right angles to the connector surfaces on the posts of the cell. When the lifting bar edges are in full engagement with the cell slots, lift the cell. Inspect the bottom of each cell for any foreign matter which may cause damage to the cell when lowered onto the floor (at the predesignated location). Be sure the polarity of the cell is facing in the correct direction.

Subsequent cells will be handled in the same manner. The nominal clearance between cells is 5/16" at the top. Due to irregularities in the cell dimensions, they should be located by center-to-center dimensions using the posts as reference points. Spacing is controlled by the solid intercell connectors.

There will be a slight settling of the cells as the rubber pads on the bottom of the jar gradually conform to the floor surface. After they are properly placed, allow the cells to settle over night. Then, should it be necessary to shim any cell, use thin strips of rubber or plastic.

8.3 CONNECTING CELLS

When the cells are ready to be connected, see Section 3.4 - Preparing Contacting Surfaces, Section 3.5 - Coating Surfaces with NO-OX-ID Grease, and Section 3.6 - Cell Interconnections.

When all the cells are connected, recheck the polarity of each cell and make sure that all connecting bolts are tight. As a further check, read the voltage of the total number of cells in the battery with a DC voltmeter. It should be 2.05 times the total number of cells in the battery. If the reading is less than this, either one or more cell is installed backwards or the voltmeter is incorrect. Recheck polarities of the cells.

Next, unpack the carton and remove the shipping vent caps from cells. Install one float assembly (tube housing and float indicator) in the back opening, and a filling funnel in the front opening. Also, on RHC type cells, remove the small "blind" vents in the opposite corners and install the long, black, plastic gravity reading tubes in these holes (only calcium batteries are provided with these additional openings.)

8.4 CONNECTING BATTERY TO CHARGER

Only direct current (DC) is used for charging. Connect the **positive** terminal of the battery **to** the **positive** of the charger or system, and the **negative** terminal of the battery **to** the **negative** of the charger or the system.

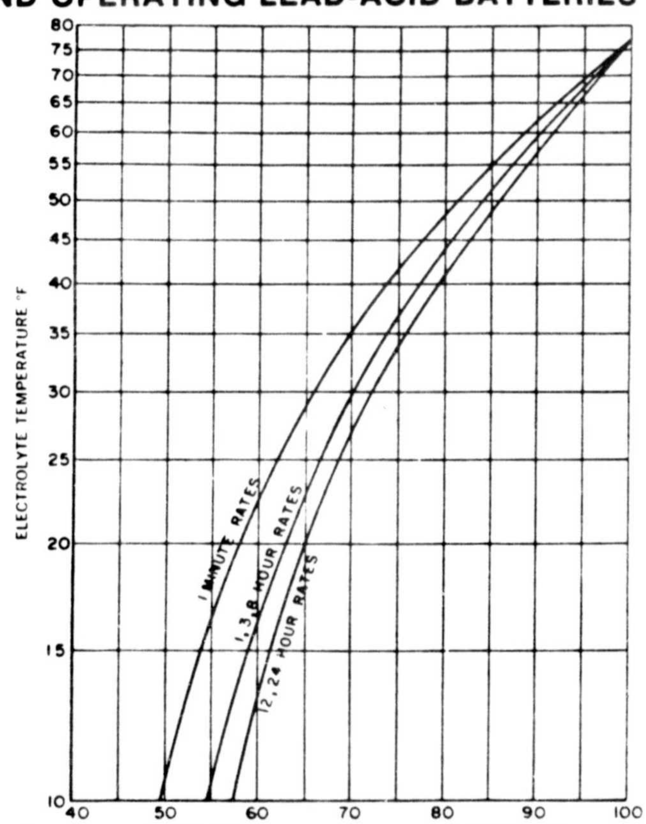
Do not add water to cells to raise float level indicators until battery has received an initial charge. The normal electrolyte level is indicated as the length of exposed color floating. If more than 1" of red is showing prior to charge, remove some electrolyte to avoid a possibility of acid loss during charge. See Section 4.0 and 5.7 for more details on initial float and equalizing charge.

USEFUL INFORMATION FOR STORING AND OPERATING LEAD-ACID BATTERIES

FREEZING POINT OF AQUEOUS SOLUTIONS OF SULFURIC ACID

Care must be taken to avoid freezing the electrolyte either in operation or storage. If it does freeze, irreparable damage may result.

Freezing Points		
Specific Gravity at 15° C	**Centigrade**	**Fahrenheit**
1.000	**0**	**+32**
1.050	**- 3.3**	**+26**
1.100	**- 7.7**	**+18**
1.150	**-15**	**+ 5**
1.200	**-27**	**-17**
1.250	**-52**	**-61**
1.300	**-70**	**-95**
1.350	**-49**	**-56**
1.400	**-36**	**-33**



BATTERY CAPACITY vs. OPERATING TEMPERATURE
PERCENT OF RATED 77°F AMPERES

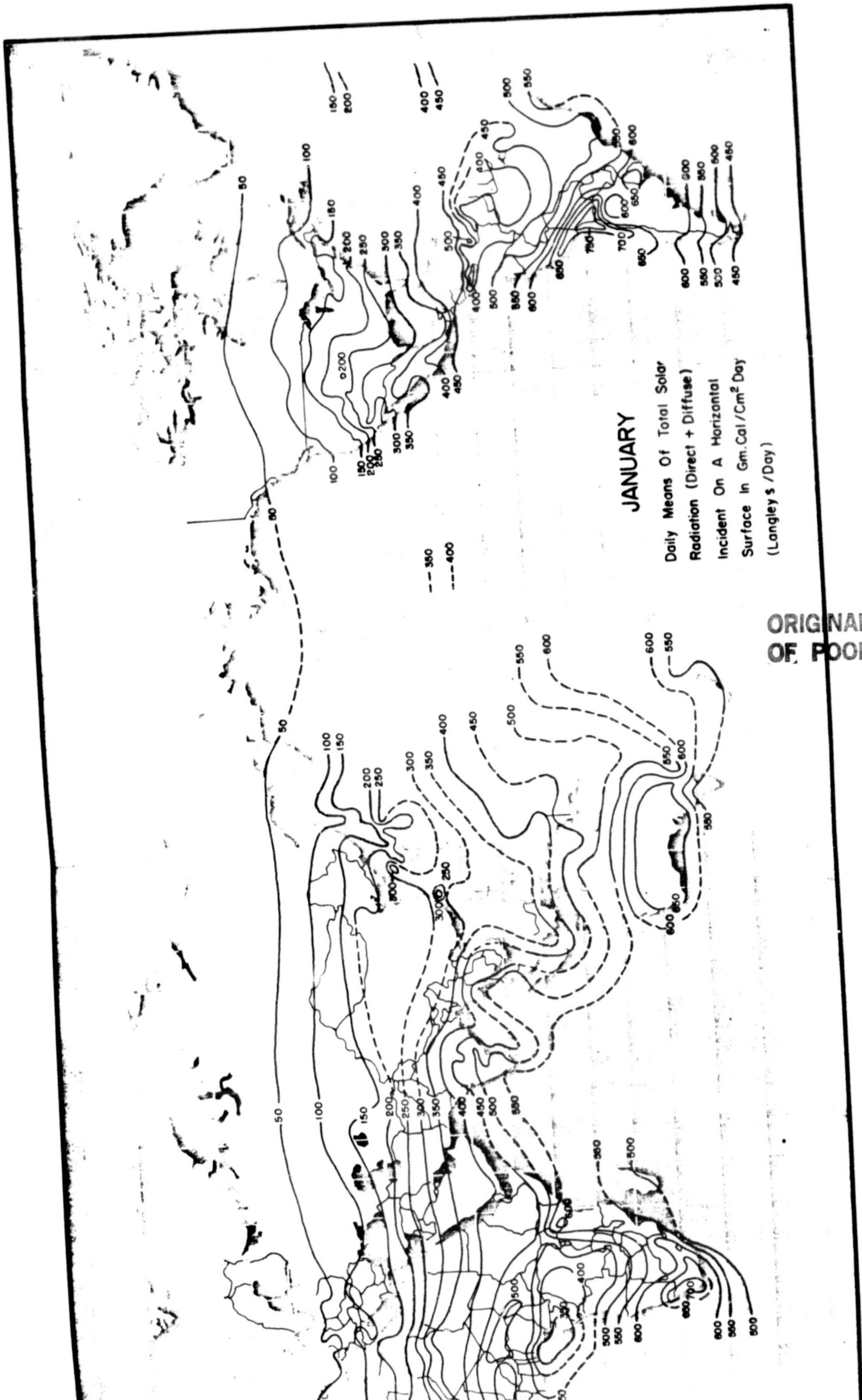
Figure 13

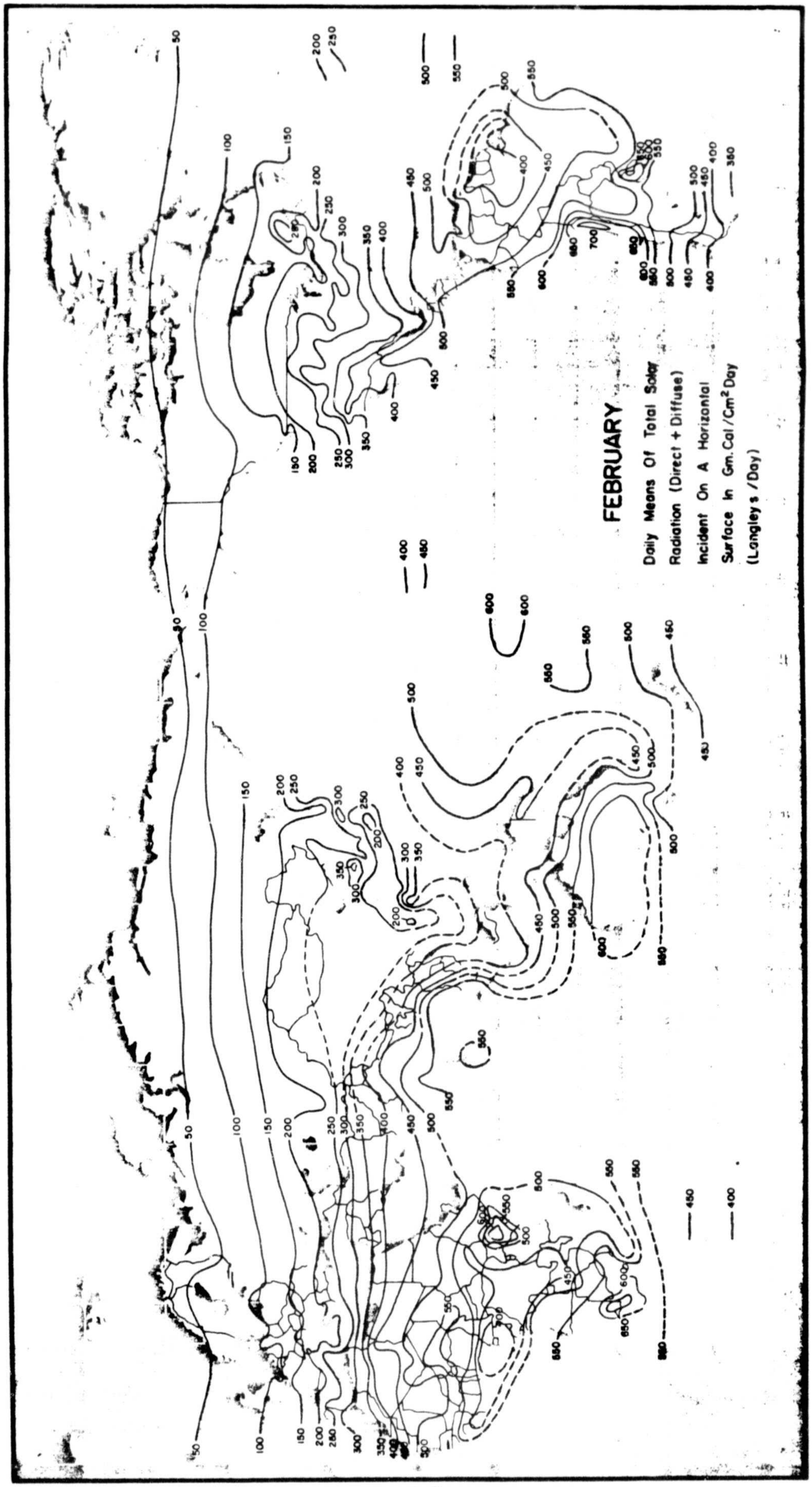
APPENDIX G

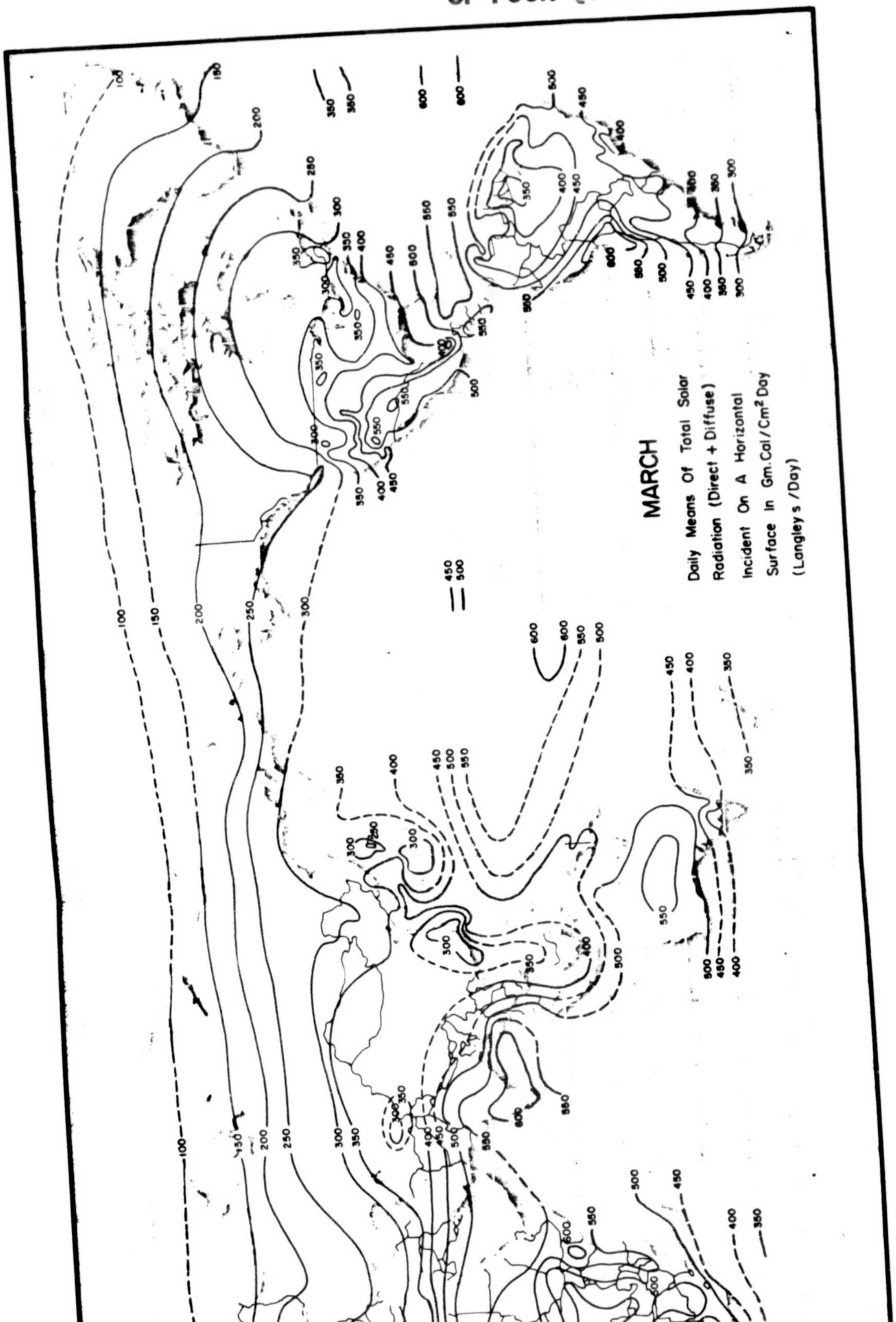
Maps of World Distribution of Solar Radiation

from:

George Löff, John Duffie, Clayton Smith, "World Distribution of Solar Radiation," University of Wisconsin College of Engineering, Engineering Station Report 21. University of Wisconsin Solar Energy Laboratory, July 1966.

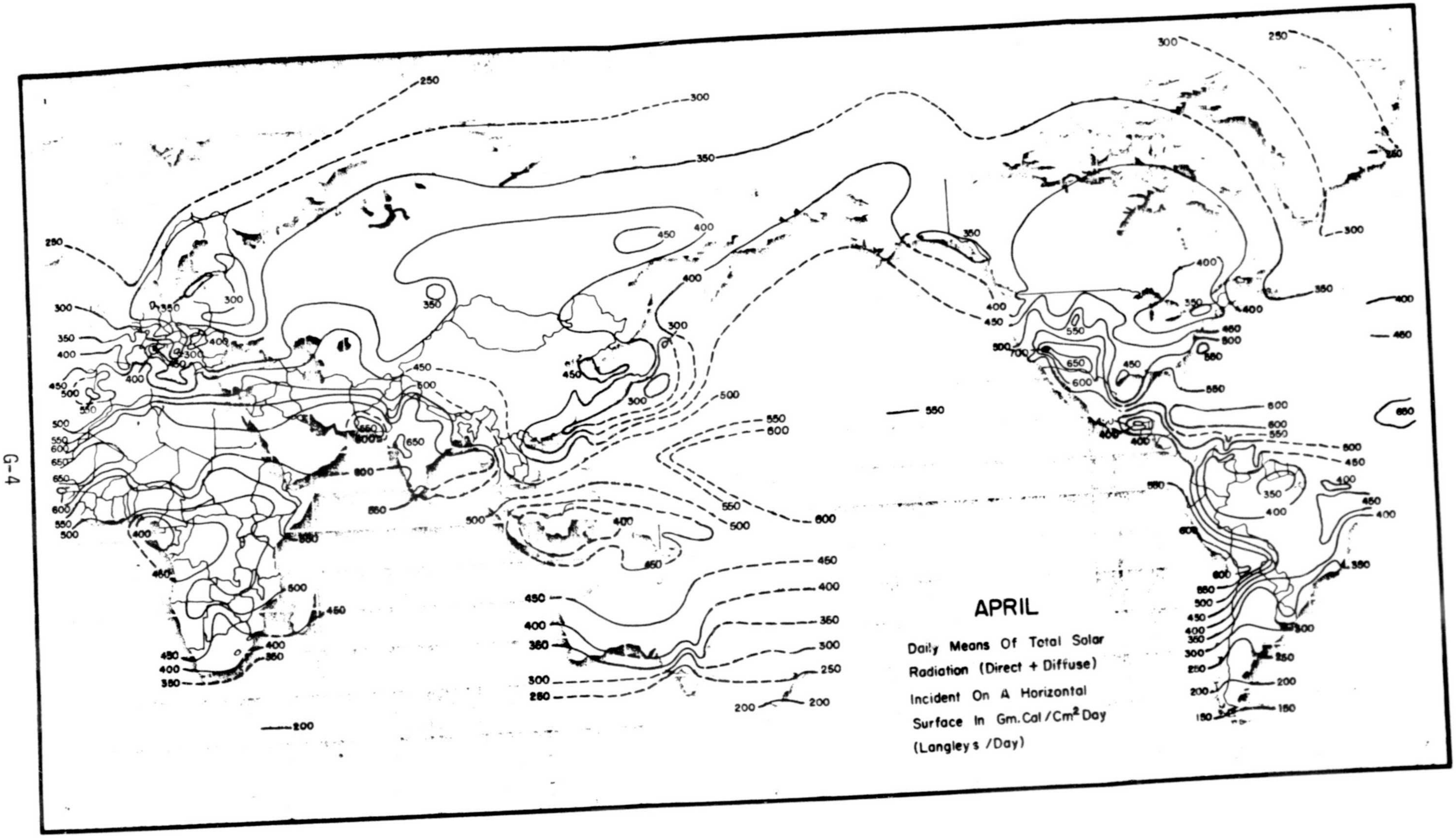

JANUARY
Daily Means Of Total Solar Radiation (Direct + Diffuse) Incident On A Horizontal Surface In Gm.Cal/Cm² Day (Langley's /Day)


FEBRUARY
Daily Means Of Total Solar
Radiation (Direct + Diffuse)
Incident On A Horizontal
Surface In Gm.Cal/Cm² Day
(Langley's /Day)



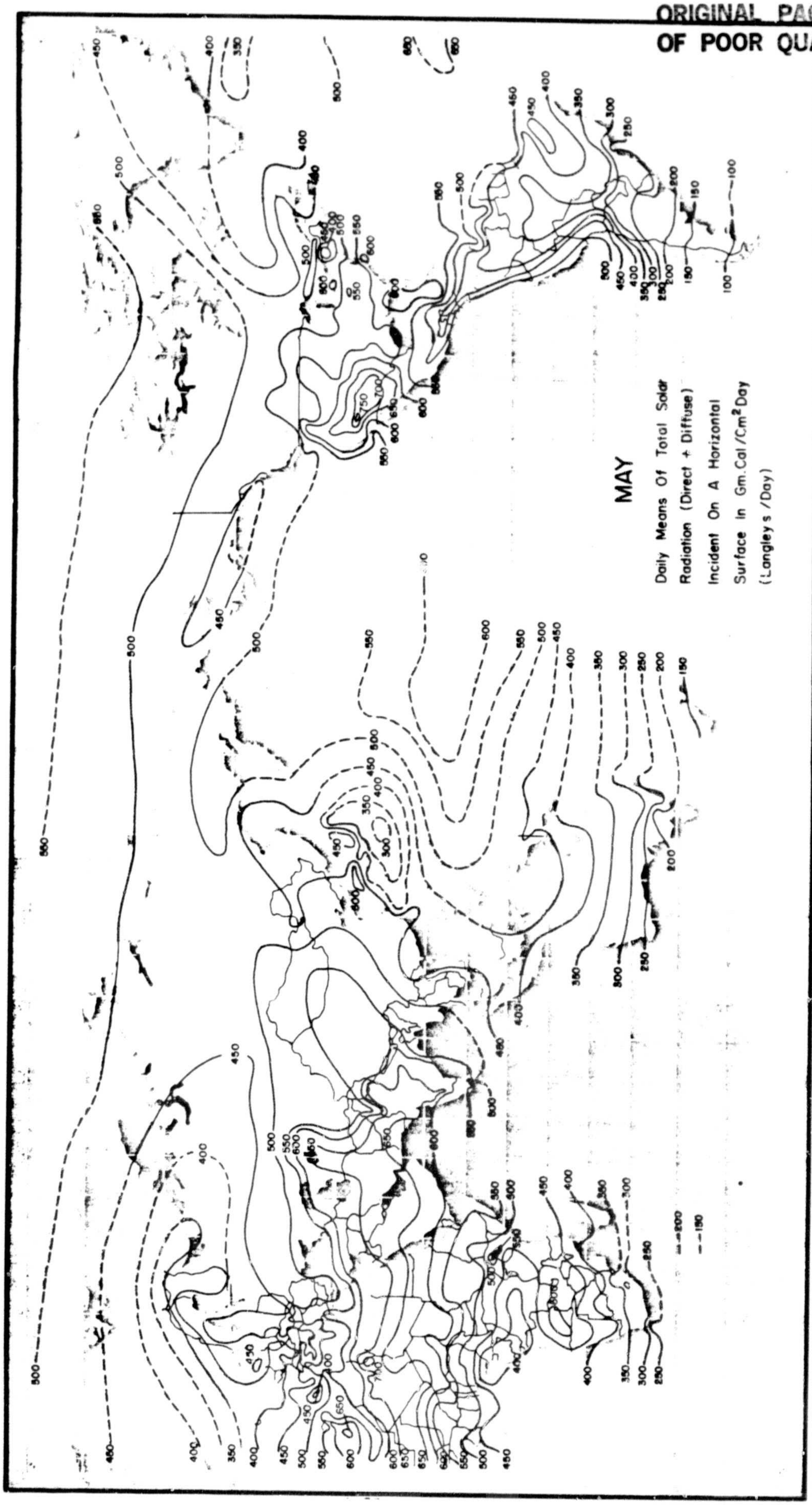
MARCH

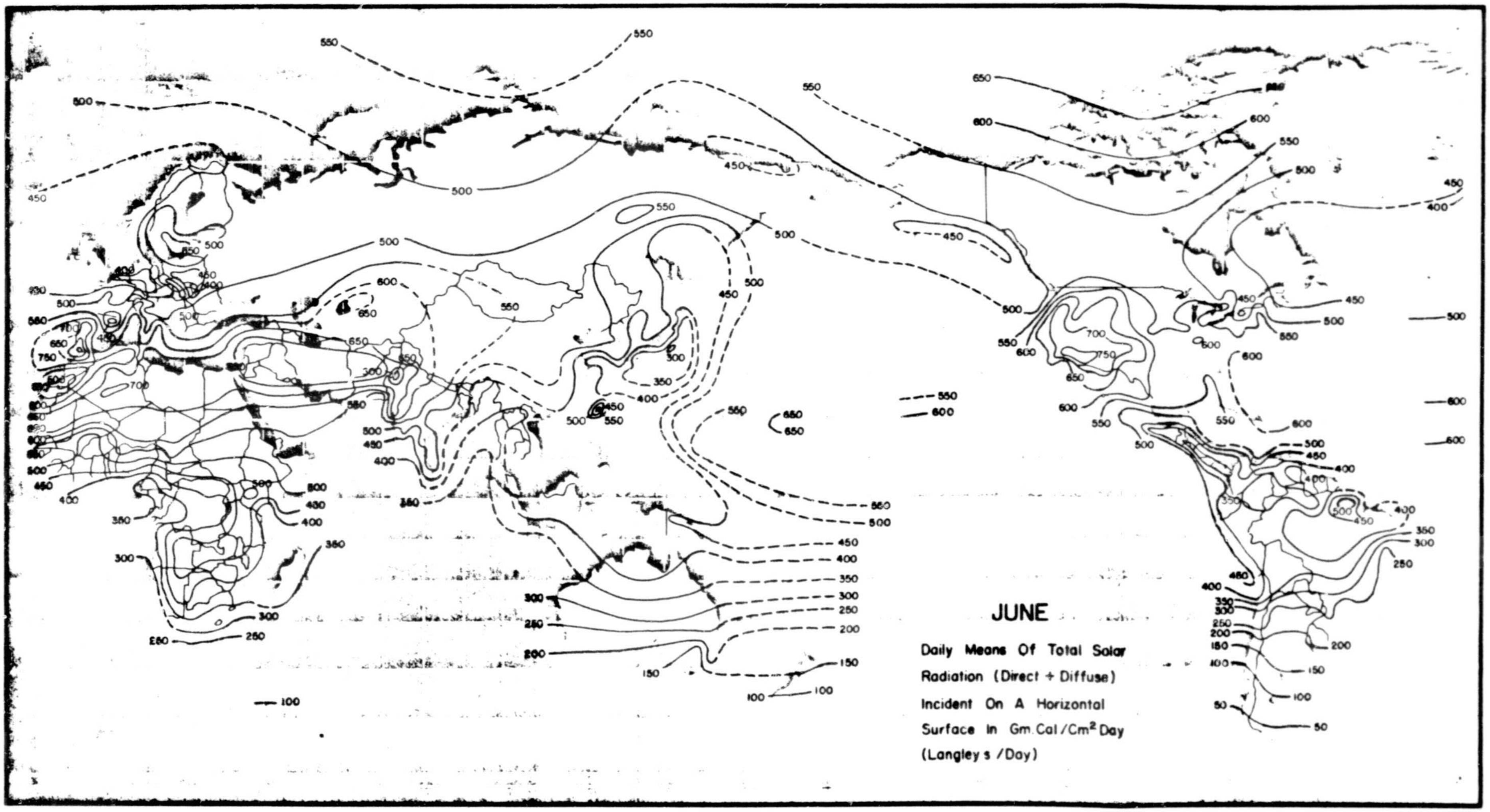
Daily Means Of Total Solar Radiation (Direct + Diffuse) Incident On A Horizontal Surface In Gm.Cal/Cm^2 Day (Langley s /Day)



APRIL

Daily Means Of Total Solar Radiation (Direct + Diffuse) Incident On A Horizontal Surface In Gm. Cal / Cm^2 Day (Langleys / Day)


MAY
Daily Means Of Total Solar
Radiation (Direct + Diffuse)
Incident On A Horizontal
Surface In Gm.Cal/Cm² Day
(Langleys /Day)


JUNE
Daily Means Of Total Solar Radiation (Direct + Diffuse) Incident On A Horizontal Surface In Gm.Cal/Cm² Day (Langleys /Day)

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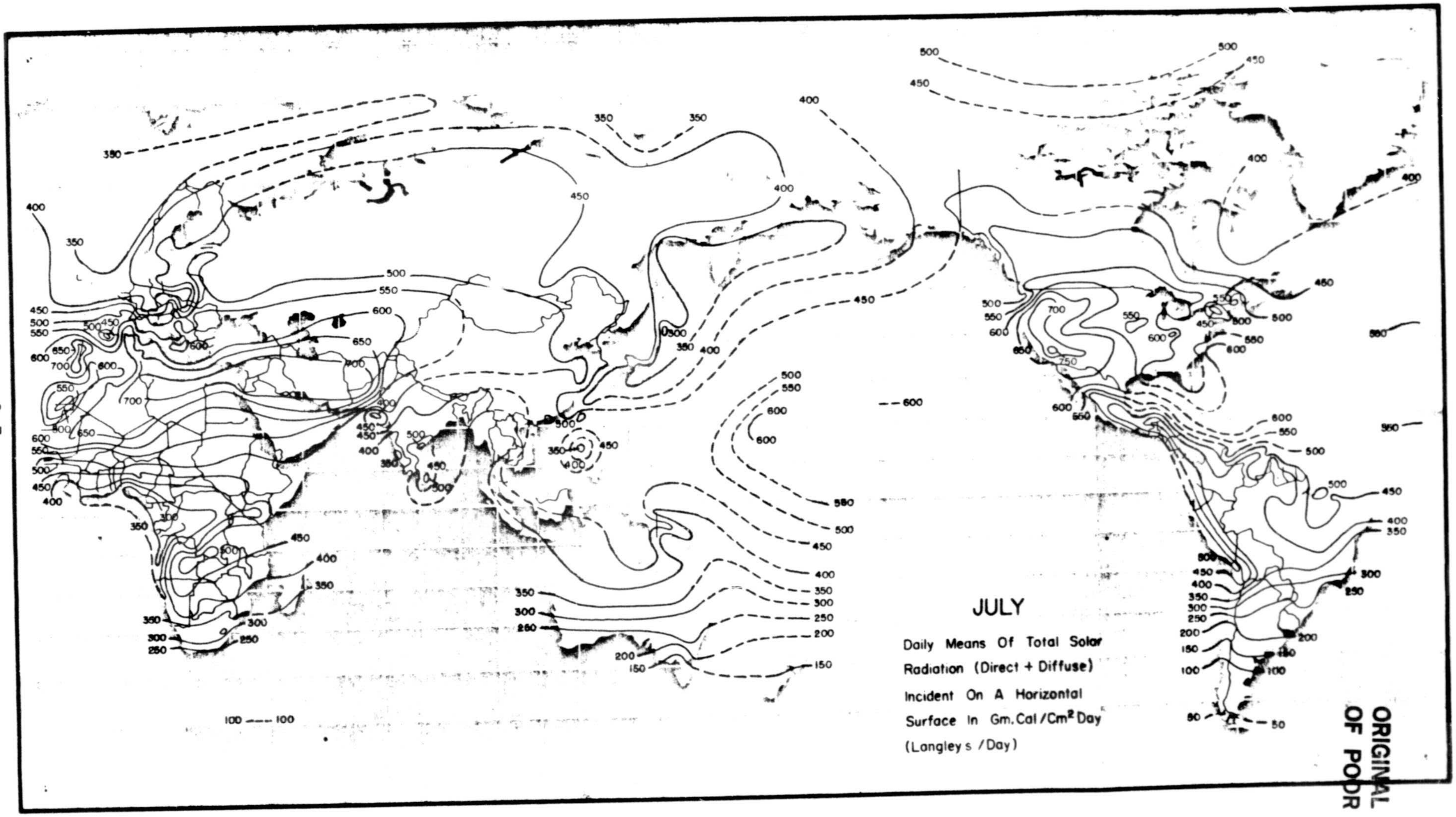
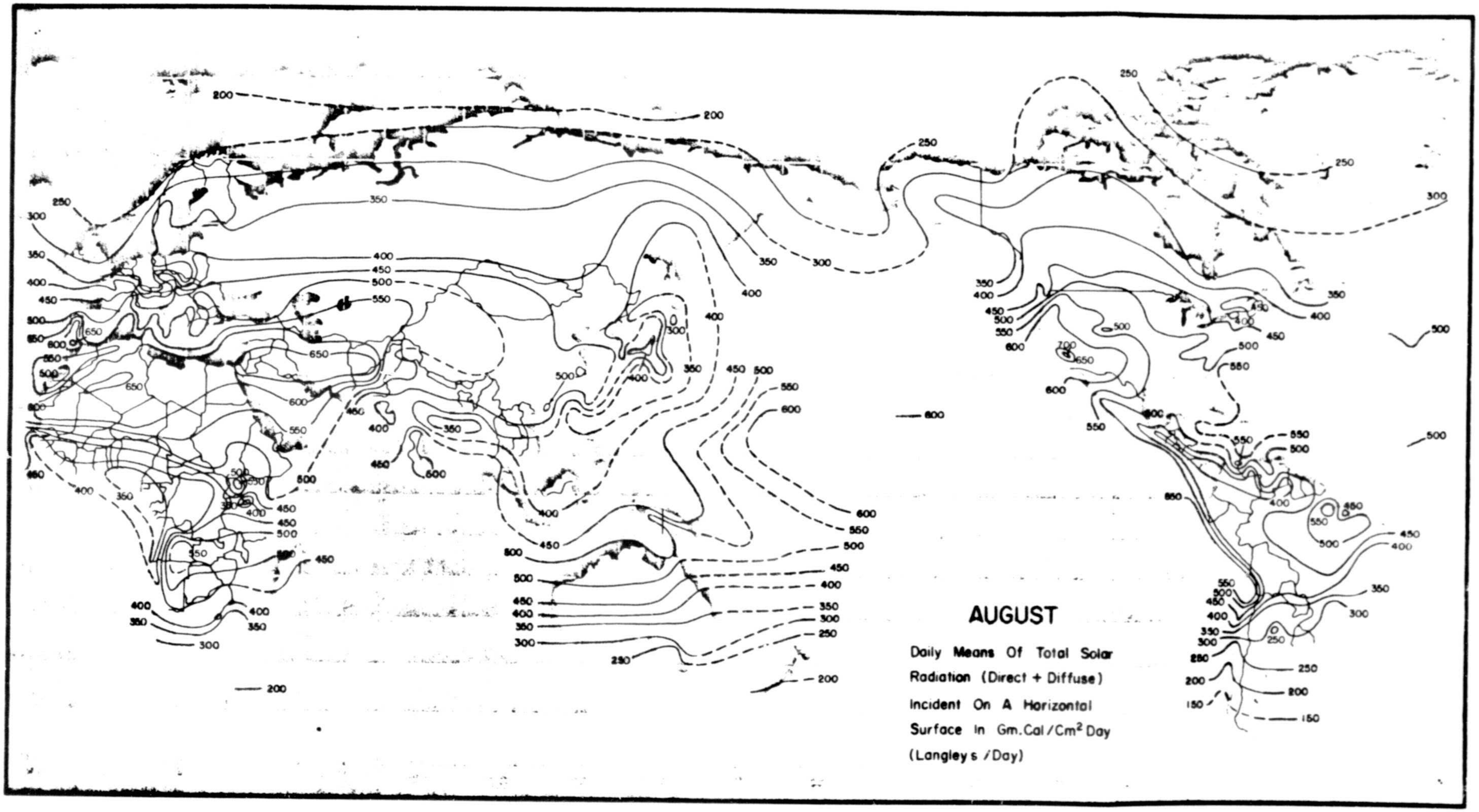
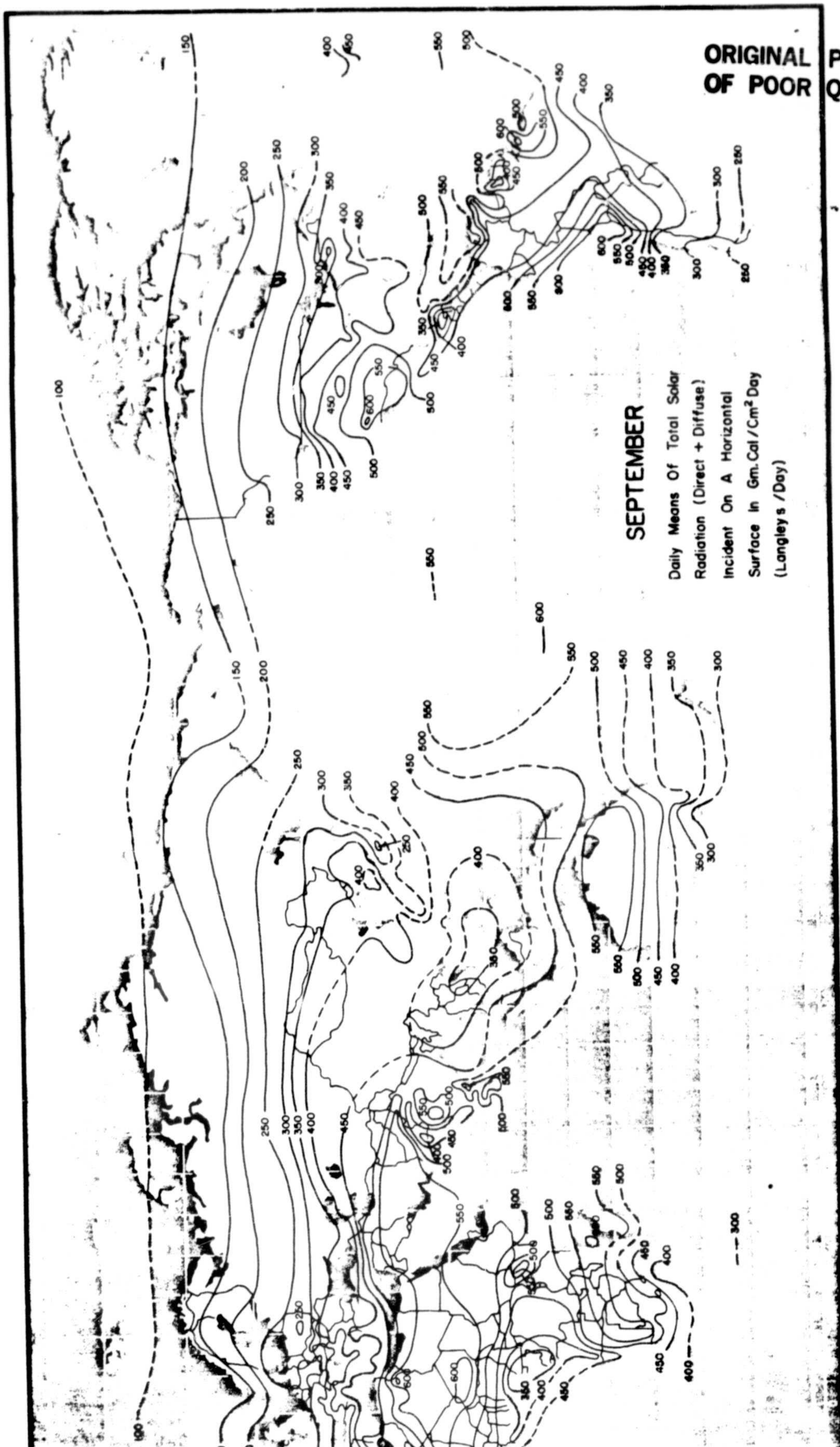
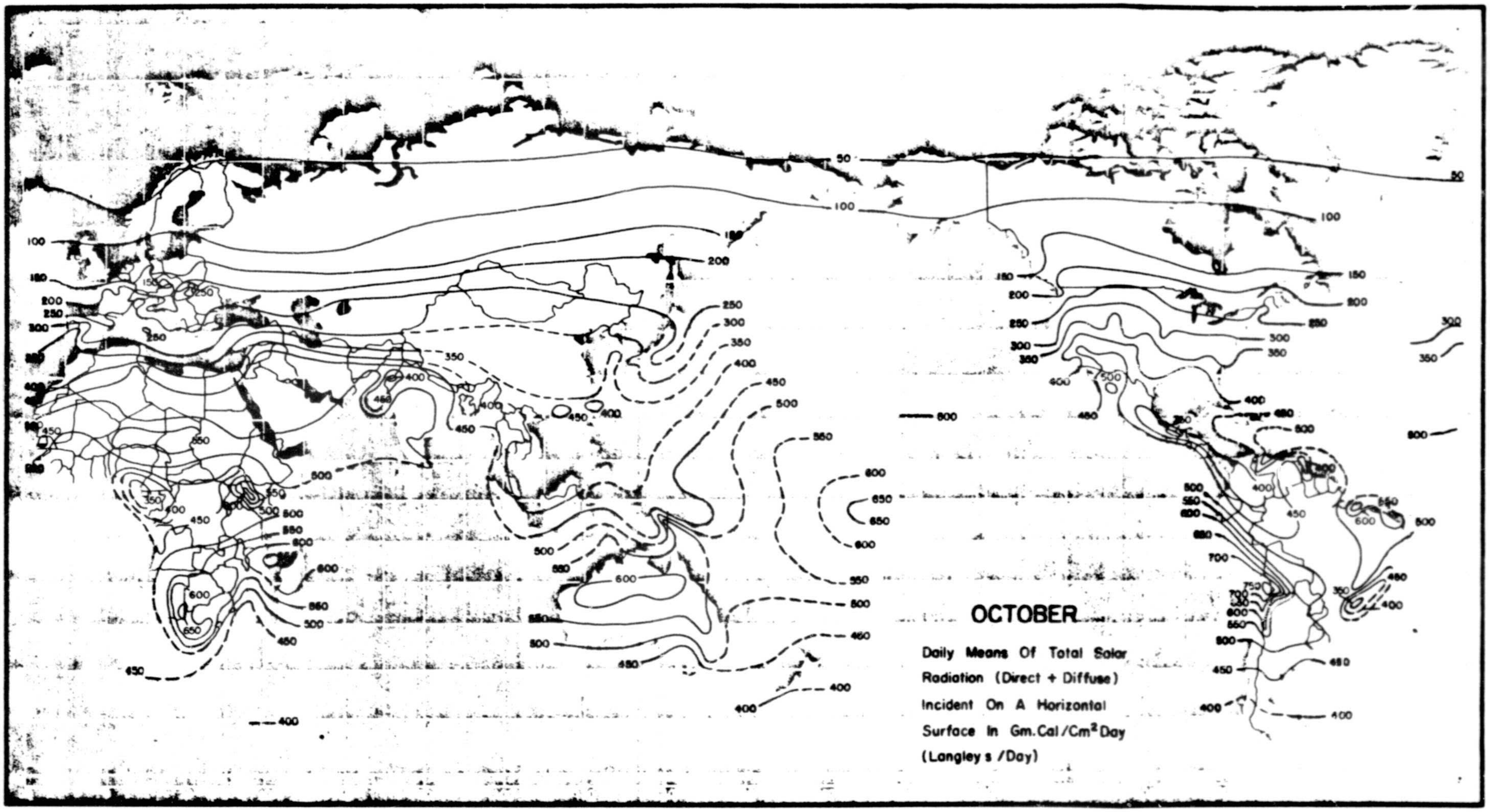




AUGUST

Daily Means Of Total Solar Radiation (Direct + Diffuse) Incident On A Horizontal Surface In Gm.Cal/Cm^2 Day (Langleys/Day)


SEPTEMBER
Daily Means Of Total Solar Radiation (Direct + Diffuse) Incident On A Horizontal Surface In Gm. Cal/Cm² Day (Langleys/Day)



OCTOBER

Daily Means Of Total Solar Radiation (Direct + Diffuse) Incident On A Horizontal Surface In Gm.Cal/Cm^2 Day (Langley s /Day)

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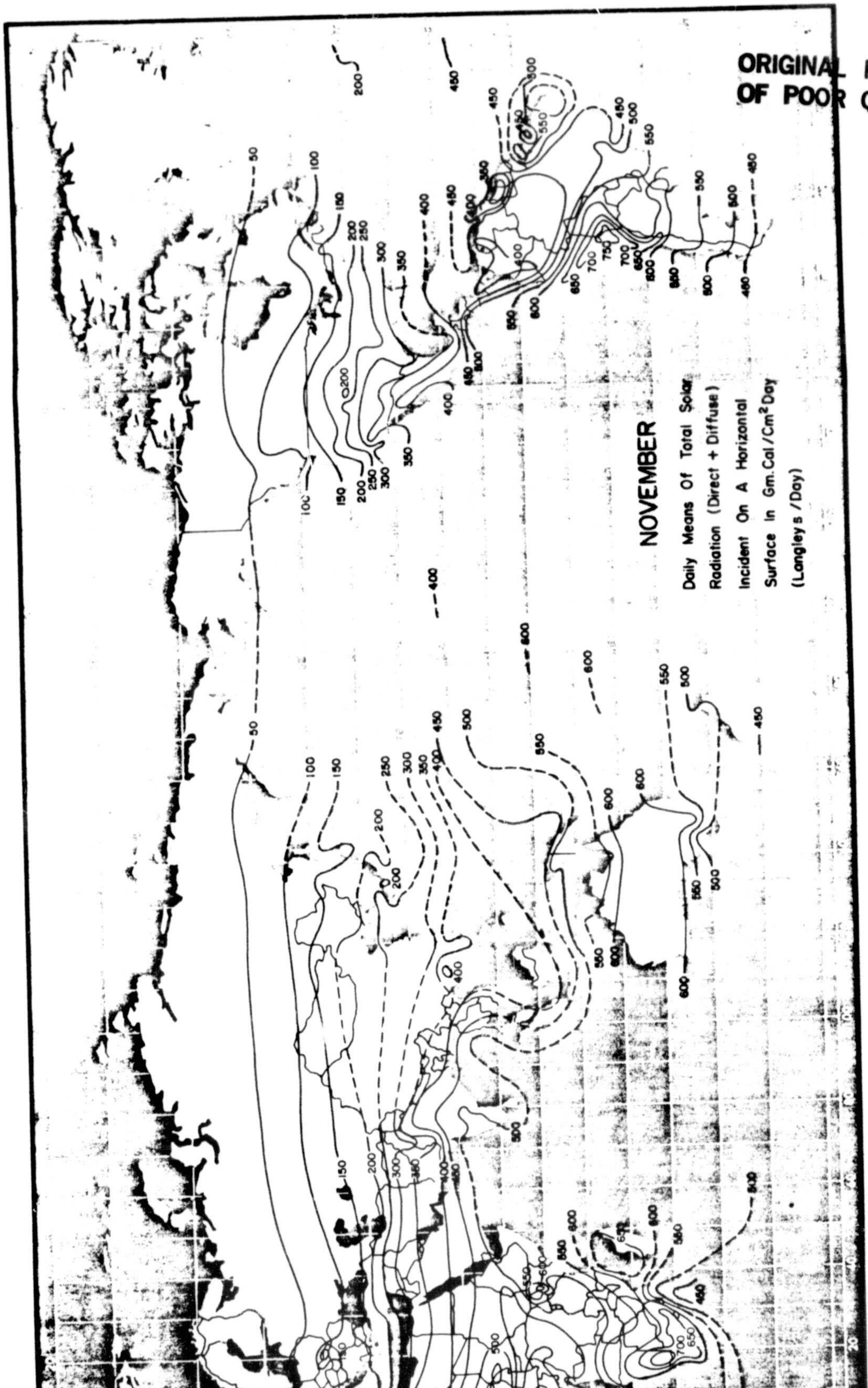

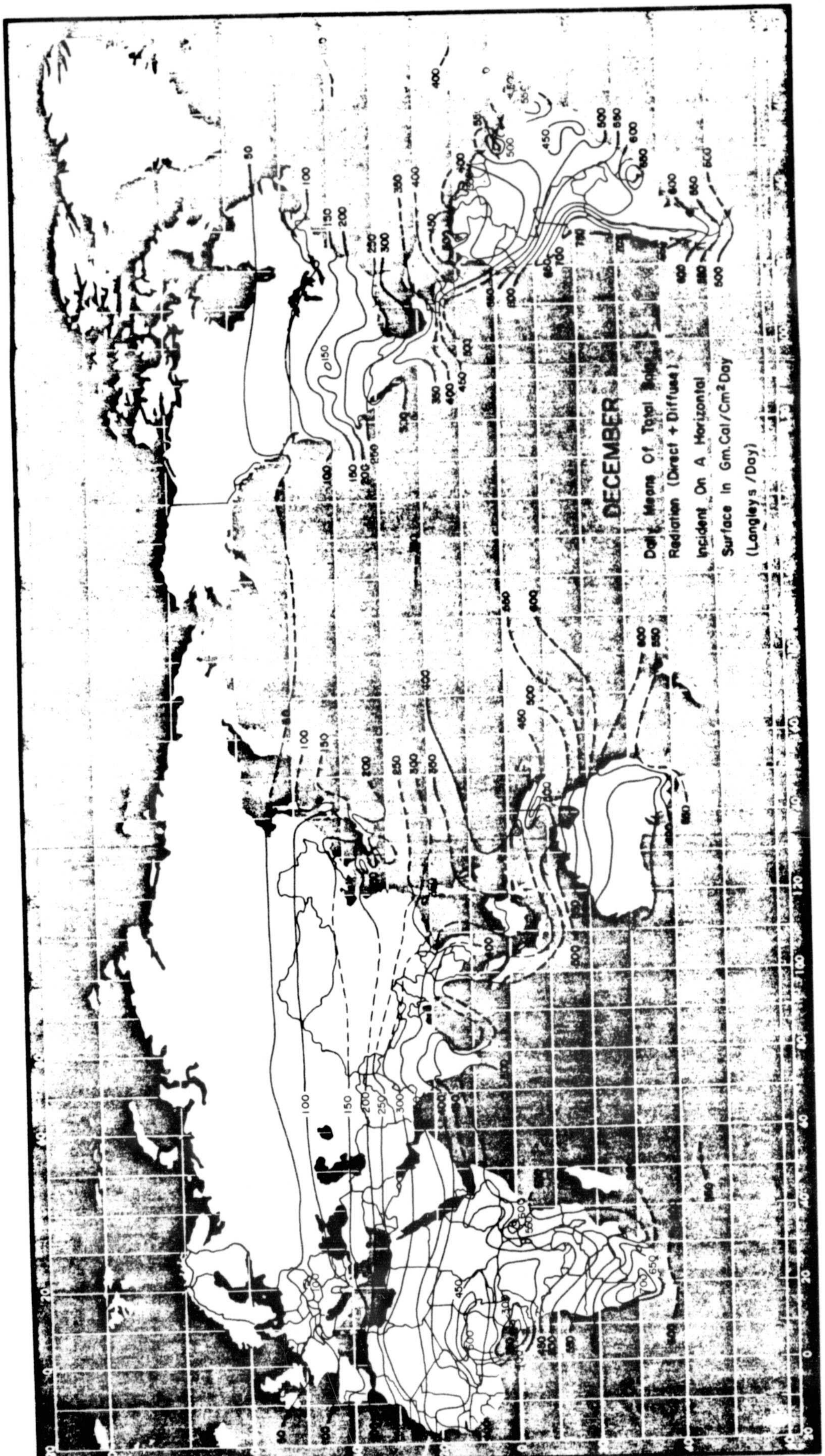
DECEMBER
Daily Means Of Total
Radiation (Direct + Diffuse)
Incident On A Horizontal
Surface In Gm.Cal/Cm²Day
(Langleys /Day)

APPENDIX H

Tables of Average Daily Insolation for Selected Locations

LATITUDE(DEG)= 0.0000   REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	0.000	0.283	2.826	243.0
2	0.000	0.280	2.884	248.0
3	0.000	0.333	3.477	299.0
4	0.000	0.339	3.430	295.0
5	0.000	0.315	3.023	260.0
6	0.000	0.258	2.384	205.0
7	0.000	0.281	2.628	226.0
8	0.000	0.261	2.570	221.0
9	0.000	0.246	2.523	217.0
10	0.000	0.233	2.395	206.0
11	0.000	0.226	2.267	195.0
12	0.000	0.232	2.279	196.0

AVE. IT(KWH/DAY)= 2.724   AVE. IT(LANG/DAY)=234.2

LATITUDE(DEG)= 0.0000   REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	-23.500	0.283	2.438	209.7
2	-23.500	0.280	2.584	222.2
3	-23.500	0.333	3.260	280.3
4	-23.500	0.339	3.409	293.2
5	-23.500	0.315	3.139	270.0
6	-23.500	0.258	2.502	215.2
7	-23.500	0.281	2.744	236.0
8	-23.500	0.261	2.583	222.1
9	-23.500	0.246	2.421	208.2
10	-23.500	0.233	2.197	188.9
11	-23.500	0.226	2.005	172.4
12	-23.500	0.232	1.976	169.9

AVE. IT(KWH/DAY)= 2.605   AVE. IT(LANG/DAY)=224.0

LATITUDE(DEG)= 0.0000   REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	23.500	0.283	2.948	253.5
2	23.500	0.280	2.905	249.8
3	23.500	0.333	3.337	287.0
4	23.500	0.339	3.102	266.8
5	23.500	0.315	2.614	224.8
6	23.500	0.258	2.049	176.2
7	23.500	0.281	2.266	194.9
8	23.500	0.261	2.312	198.8
9	23.500	0.246	2.384	205.0
10	23.500	0.233	2.369	203.8
11	23.500	0.226	2.324	199.9
12	23.500	0.232	2.379	204.6

AVE. IT(KWH/DAY)= 2.582   AVE. IT(LANG/DAY)=222.1

LATITUDE(DEG)= 0.0000   REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)	S(KWH/DAY)	S(LANG/DAY)
1	23.500	0.283	2.951	253.8	3.689	317.3
2	23.500	0.280	2.910	250.2	2.606	224.1
3	23.500	0.333	3.333	286.6	2.166	186.2
4	-23.500	0.339	3.412	293.4	2.241	192.7
5	-23.500	0.315	3.135	269.6	2.226	191.5
6	-23.500	0.258	2.499	214.9	2.330	200.4
7	-23.500	0.281	2.747	236.2	2.190	188.4
8	-23.500	0.261	2.583	222.1	2.142	184.2
9	-23.500	0.246	2.419	208.0	2.039	175.3
10	23.500	0.233	2.370	203.8	2.171	186.7
11	23.500	0.226	2.322	199.7	2.273	195.5
12	23.500	0.232	2.382	204.9	2.306	198.3

AVE. IT(KWH/DAY)= 2.755   AVE. IT(LANG/DAY)=236.9

FIGURE H-1 DAILY AVERAGE INSOLATION: LA CONCORDIA, ECUADOR, 0°N 79°20'W

LATITUDE(DEG)=-0.2833 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	0.000	0.505	5.062	435.3
2	0.000	0.490	5.064	435.5
3	0.000	0.397	4.140	356.1
4	0.000	0.428	4.329	372.3
5	0.000	0.437	4.178	359.3
6	0.000	0.476	4.379	376.6
7	0.000	0.505	4.713	405.3
8	0.000	0.584	5.739	493.5
9	0.000	0.449	4.600	395.6
10	0.000	0.467	4.809	413.6
11	0.000	0.484	4.865	418.4
12	0.000	0.487	4.806	413.3

AVE. IT(KWH/DAY)= 4.724 AVE. IT(LANG/DAY)=406.2

LATITUDE(DEG)=-0.2833 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	-23.500	0.505	4.121	354.4
2	-23.500	0.490	4.378	376.5
3	-23.500	0.397	3.870	332.9
4	-23.500	0.428	4.327	372.1
5	-23.500	0.437	4.418	380.0
6	-23.500	0.476	4.791	412.0
7	-23.500	0.505	5.107	439.2
8	-23.500	0.584	5.932	510.1
9	-23.500	0.449	4.402	378.5
10	-23.500	0.467	4.270	367.2
11	-23.500	0.484	4.037	347.2
12	-23.500	0.487	3.858	331.8

AVE. IT(KWH/DAY)= 4.459 AVE. IT(LANG/DAY)=383.5

LATITUDE(DEG)=-0.2833 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	23.500	0.505	5.460	469.6
2	23.500	0.490	5.190	446.3
3	23.500	0.397	3.967	341.1
4	23.500	0.428	3.863	332.2
5	23.500	0.437	3.500	301.0
6	23.500	0.476	3.513	302.1
7	23.500	0.505	3.816	328.2
8	23.500	0.584	4.882	419.9
9	23.500	0.449	4.289	368.8
10	23.500	0.467	4.816	414.2
11	23.500	0.484	5.172	444.7
12	23.500	0.487	5.253	451.7

AVE. IT(KWH/DAY)= 4.477 AVE. IT(LANG/DAY)=385.0

LATITUDE(DEG)=-0.2833 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)	S(KWH/DAY)	S(LANG/DAY)
1	23.500	0.505	5.460	469.6	2.391	205.6
2	23.500	0.490	5.190	446.3	2.295	197.4
3	23.500	0.397	3.967	341.1	2.186	188.0
4	-23.500	0.428	4.327	372.1	2.272	195.4
5	-23.500	0.437	4.418	380.0	2.348	201.9
6	-23.500	0.476	4.791	412.0	2.312	198.8
7	-23.500	0.505	5.107	439.2	2.242	192.8
8	-23.500	0.584	5.932	510.1	2.190	188.3
9	-23.500	0.449	4.402	378.5	2.120	182.3
10	23.500	0.467	4.816	414.2	2.267	195.0
11	23.500	0.484	5.172	444.7	2.388	205.4
12	23.500	0.487	5.253	451.7	2.441	209.9

AVE. IT(KWH/DAY)= 4.903 AVE. IT(LANG/DAY)=421.6

FIGURE H-2 AVERAGE DAILY INSOLATION: QUITO, ECUADOR, 0°17'S 78°32'W

LATITUDE(DEG)= 7.7500 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	0.000	0.498	4.535	390.0
2	0.000	0.514	5.000	430.0
3	0.000	0.500	5.116	440.0
4	0.000	0.504	5.233	450.0
5	0.000	0.468	4.767	410.0
6	0.000	0.465	4.651	400.0
7	0.000	0.509	5.116	440.0
8	0.000	0.534	5.465	470.0
9	0.000	0.557	5.698	490.0
10	0.000	0.545	5.349	460.0
11	0.000	0.530	4.884	420.0
12	0.000	0.485	4.302	370.0

AVE. IT(KWH/DAY)= 5.010 AVE. IT(LANG/DAY)=430.8

LATITUDE(DEG)= 7.7500 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	7.750	0.498	4.781	411.2
2	7.750	0.514	5.175	445.1
3	7.750	0.500	5.164	444.1
4	7.750	0.504	5.152	443.1
5	7.750	0.468	4.608	396.3
6	7.750	0.465	4.454	383.0
7	7.750	0.509	4.910	422.3
8	7.750	0.534	5.334	458.7
9	7.750	0.557	5.700	490.2
10	7.750	0.545	5.496	472.7
11	7.750	0.530	5.134	441.5
12	7.750	0.485	4.561	392.2

AVE. IT(KWH/DAY)= 5.039 AVE. IT(LANG/DAY)=433.4

LATITUDE(DEG)= 7.7500 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	-15.750	0.498	3.881	333.7
2	-15.750	0.514	4.460	383.6
3	-15.750	0.500	4.823	414.8
4	-15.750	0.504	5.195	446.8
5	-15.750	0.468	4.915	422.7
6	-15.750	0.465	4.882	419.8
7	-15.750	0.509	5.342	459.4
8	-15.750	0.534	5.520	474.7
9	-15.750	0.557	5.468	470.3
10	-15.750	0.545	4.845	416.7
11	-15.750	0.530	4.204	361.5
12	-15.750	0.485	3.637	312.8

AVE. IT(KWH/DAY)= 4.764 AVE. IT(LANG/DAY)=409.7

LATITUDE(DEG)= 7.7500 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	31.250	0.498	5.138	441.9
2	31.250	0.514	5.292	455.1
3	31.250	0.500	4.914	422.6
4	31.250	0.504	4.537	390.1
5	31.250	0.468	3.833	329.6
6	31.250	0.465	3.598	309.4
7	31.250	0.509	3.983	342.5
8	31.250	0.534	4.561	392.2
9	31.250	0.557	5.265	452.8
10	31.250	0.545	5.502	473.2
11	31.250	0.530	5.470	470.4
12	31.250	0.485	4.972	427.6

AVE. IT(KWH/DAY)= 4.755 AVE. IT(LANG/DAY)=409.0

LATITUDE(DEG)= 7.7500 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)	S(KWH/DAY)	S(LANG/DAY)
1	31.250	0.498	5.144	442.4	2.372	204.0
2	31.250	0.514	5.287	454.7	2.300	197.8
3	31.250	0.500	4.918	423.0	2.045	175.9
4	-15.750	0.504	5.198	447.0	2.133	183.4
5	-15.750	0.468	4.918	422.9	2.324	199.8
6	-15.750	0.465	4.877	419.5	2.354	202.5
7	-15.750	0.509	5.341	459.3	2.258	194.2
8	-15.750	0.534	5.524	475.1	2.207	189.8
9	-15.750	0.557	5.467	470.2	2.021	173.8
10	31.250	0.545	5.507	473.6	2.248	193.3
11	31.250	0.530	5.473	470.6	2.402	206.5
12	31.250	0.485	4.975	427.9	2.425	208.6

AVE. IT(KWH/DAY)= 5.219 AVE. IT(LANG/DAY)=448.8

FIGURE H-3 AVERAGE DAILY INSOLATION: GEORGETOWN, GUYANA, 7°45'N 58°04'W

LATITUDE(DEG)= 5.9667 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	0.000	0.433	4.040	347.4
2	0.000	0.421	4.156	357.4
3	0.000	0.427	4.398	378.2
4	0.000	0.416	4.303	370.1
5	0.000	0.453	4.560	392.2
6	0.000	0.442	4.345	373.7
7	0.000	0.451	4.467	384.2
8	0.000	0.437	4.443	382.1
9	0.000	0.419	4.294	369.3
10	0.000	0.427	4.246	365.2
11	0.000	0.437	4.116	354.0
12	0.000	0.455	4.144	356.4

AVE. IT(KWH/DAY)= 4.293 AVE. IT(LANG/DAY)=369.2

LATITUDE(DEG)= 5.9667 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	5.967	0.433	4.188	360.2
2	5.967	0.421	4.250	365.5
3	5.967	0.427	4.423	380.3
4	5.967	0.416	4.254	365.8
5	5.967	0.453	4.441	381.9
6	5.967	0.442	4.203	361.5
7	5.967	0.451	4.334	372.7
8	5.967	0.437	4.366	375.5
9	5.967	0.419	4.290	369.0
10	5.967	0.427	4.319	371.4
11	5.967	0.437	4.253	365.8
12	5.967	0.455	4.321	371.6

AVE. IT(KWH/DAY)= 4.303 AVE. IT(LANG/DAY)=370.1

LATITUDE(DEG)= 5.9667 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	-18.500	0.433	3.423	294.4
2	-18.500	0.421	3.691	317.5
3	-18.500	0.427	4.126	354.8
4	-18.500	0.416	4.262	366.5
5	-18.500	0.453	4.723	406.1
6	-18.500	0.442	4.590	394.7
7	-18.500	0.451	4.677	402.2
8	-18.500	0.437	4.479	385.2
9	-18.500	0.419	4.113	353.7
10	-18.500	0.427	3.838	330.1
11	-18.500	0.437	3.524	303.1
12	-18.500	0.455	3.439	295.7

AVE. IT(KWH/DAY)= 4.074 AVE. IT(LANG/DAY)=350.3

LATITUDE(DEG)= 5.9667 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	29.500	0.433	4.462	383.8
2	29.500	0.421	4.313	370.9
3	29.500	0.427	4.213	362.3
4	29.500	0.416	3.785	325.5
5	29.500	0.453	3.706	318.7
6	29.500	0.442	3.415	293.7
7	29.500	0.451	3.562	306.3
8	29.500	0.437	3.786	325.6
9	29.500	0.419	3.985	342.7
10	29.500	0.427	4.297	369.5
11	29.500	0.437	4.481	385.4
12	29.500	0.455	4.692	403.5

AVE. IT(KWH/DAY)= 4.058 AVE. IT(LANG/DAY)=349.0

FIGURE H-4 AVERAGE DAILY INSOLATION: MAZARUNI, GUYANA, 5°58'N 59°37'W

LATITUDE(DEG)=-1.3000 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	0.000	0.641	6.488	558.0
2	0.000	0.665	6.919	595.0
3	0.000	0.623	6.500	559.0
4	0.000	0.561	5.651	486.0
5	0.000	0.511	4.837	416.0
6	0.000	0.508	4.616	397.0
7	0.000	0.408	3.767	324.0
8	0.000	0.436	4.256	366.0
9	0.000	0.527	5.395	464.0
10	0.000	0.553	5.721	492.0
11	0.000	0.557	5.651	486.0
12	0.000	0.608	6.070	522.0

AVE. IT(KWH/DAY)= 5.489 AVE. IT(LANG/DAY)=472.1

LATITUDE(DEG)=-1.3000 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	-24.833	0.641	5.086	437.4
2	-24.833	0.665	5.805	499.2
3	-24.833	0.623	5.991	515.2
4	-24.833	0.561	5.691	489.5
5	-24.833	0.511	5.188	446.2
6	-24.833	0.508	5.110	439.4
7	-24.833	0.408	4.044	347.8
8	-24.833	0.436	4.361	375.1
9	-24.833	0.527	5.149	442.8
10	-24.833	0.553	5.000	430.0
11	-24.833	0.557	4.577	393.6
12	-24.833	0.608	4.680	402.5

AVE. IT(KWH/DAY)= 5.057 AVE. IT(LANG/DAY)=434.9

LATITUDE(DEG)=-1.3000 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	22.167	0.641	7.057	606.9
2	22.167	0.665	7.141	614.2
3	22.167	0.623	6.218	534.7
4	22.167	0.561	4.994	429.5
5	22.167	0.511	4.022	345.9
6	22.167	0.508	3.710	319.1
7	22.167	0.408	3.155	271.3
8	22.167	0.436	3.728	320.6
9	22.167	0.527	5.027	432.3
10	22.167	0.553	5.744	494.0
11	22.167	0.557	6.024	518.1
12	22.167	0.608	6.691	575.4

AVE. IT(KWH/DAY)= 5.293 AVE. IT(LANG/DAY)=455.2

LATITUDE(DEG)=-1.3000 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)	S(KWH/DAY)	S(LANG/DAY)
1	22.167	0.641	7.060	607.2	2.140	184.1
2	22.167	0.665	7.138	613.9	1.809	155.6
3	22.167	0.623	6.221	535.0	1.902	163.6
4	-24.833	0.561	5.687	489.1	2.186	188.0
5	-24.833	0.511	5.189	446.3	2.255	193.9
6	-24.833	0.508	5.111	439.5	2.269	195.2
7	-24.833	0.408	4.043	347.7	2.338	201.1
8	-24.833	0.436	4.361	375.0	2.284	196.4
9	-24.833	0.527	5.146	442.6	2.029	174.5
10	22.167	0.553	5.743	493.9	2.232	192.0
11	22.167	0.557	6.024	518.1	2.410	207.3
12	22.167	0.608	6.691	575.4	2.378	204.5

AVE. IT(KWH/DAY)= 5.701 AVE. IT(LANG/DAY)=490.3

FIGURE H-5 AVERAGE DAILY INSOLATION: NAIROBI, KENYA, 1°18'S 36°45'E

LATITUDE(DEG)=-3.3833 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	0.000	0.550	5.686	489.0
2	0.000	0.574	6.035	519.0
3	0.000	0.567	5.919	509.0
4	0.000	0.536	5.337	459.0
5	0.000	0.517	4.791	412.0
6	0.000	0.531	4.698	404.0
7	0.000	0.464	4.186	360.0
8	0.000	0.451	4.337	373.0
9	0.000	0.460	4.686	403.0
10	0.000	0.497	5.186	446.0
11	0.000	0.563	5.814	500.0
12	0.000	0.580	5.919	509.0

AVE. IT(KWH/DAY)= 5.216 AVE. IT(LANG/DAY)=448.6

LATITUDE(DEG)=-3.3833 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	-3.383	0.550	5.573	479.3
2	-3.383	0.574	5.961	512.6
3	-3.383	0.567	5.910	508.3
4	-3.383	0.536	5.391	463.6
5	-3.383	0.517	4.885	420.1
6	-3.383	0.531	4.816	414.2
7	-3.383	0.464	4.274	367.5
8	-3.383	0.451	4.392	377.7
9	-3.383	0.460	4.697	404.0
10	-3.383	0.497	5.144	442.4
11	-3.383	0.563	5.708	490.9
12	-3.383	0.580	5.782	497.3

AVE. IT(KWH/DAY)= 5.211 AVE. IT(LANG/DAY)=448.2

LATITUDE(DEG)=-3.3833 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	-26.883	0.550	4.488	386.0
2	-26.883	0.574	5.079	436.8
3	-26.883	0.567	5.457	469.3
4	-26.883	0.536	5.396	464.1
5	-26.883	0.517	5.199	447.1
6	-26.883	0.531	5.295	455.4
7	-26.883	0.464	4.589	394.6
8	-26.883	0.451	4.478	385.1
9	-26.883	0.460	4.475	384.9
10	-26.883	0.497	4.535	390.0
11	-26.883	0.563	4.655	400.3
12	-26.883	0.580	4.536	390.1

AVE. IT(KWH/DAY)= 4.849 AVE. IT(LANG/DAY)=417.0

LATITUDE(DEG)=-3.3833 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	20.050	0.550	6.065	521.6
2	20.050	0.574	6.165	530.2
3	20.050	0.567	5.671	487.7
4	20.050	0.536	4.765	409.8
5	20.050	0.517	4.028	346.4
6	20.050	0.531	3.810	327.7
7	20.050	0.464	3.500	301.0
8	20.050	0.451	3.824	328.9
9	20.050	0.460	4.397	378.2
10	20.050	0.497	5.181	445.5
11	20.050	0.563	6.141	528.1
12	20.050	0.580	6.420	552.2

AVE. IT(KWH/DAY)= 4.997 AVE. IT(LANG/DAY)=429.8

FIGURE H-6 AVERAGE DAILY INSOLATION: VOI, KENYA, 3°23'S 38°34'E

LATITUDE(DEG)= -17.300 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	0.000	0.507	5.767	496.0
2	0.000	0.520	5.721	492.0
3	0.000	0.588	5.977	514.0
4	0.000	0.628	5.593	481.0
5	0.000	0.678	5.221	449.0
6	0.000	0.658	4.640	399.0
7	0.000	0.673	4.930	424.0
8	0.000	0.651	5.442	468.0
9	0.000	0.632	6.081	523.0
10	0.000	0.603	6.419	552.0
11	0.000	0.519	5.826	501.0
12	0.000	0.496	5.674	488.0

AVE. IT(KWH/DAY)= 5.608 AVE. IT(LANG/DAY)=482.2

LATITUDE(DEG)= -17.300 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	-17.300	0.507	5.343	459.5
2	-17.300	0.520	5.488	471.9
3	-17.300	0.588	6.055	520.7
4	-17.300	0.628	6.075	522.5
5	-17.300	0.678	6.070	522.1
6	-17.300	0.658	5.572	479.2
7	-17.300	0.673	5.834	501.8
8	-17.300	0.651	6.068	521.9
9	-17.300	0.632	6.321	543.6
10	-17.300	0.603	6.255	537.9
11	-17.300	0.519	5.439	467.7
12	-17.300	0.496	5.206	447.7

AVE. IT(KWH/DAY)= 5.811 AVE. IT(LANG/DAY)=499.7

LATITUDE(DEG)= -17.300 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	5.333	0.507	5.834	501.7
2	5.333	0.520	5.724	492.2
3	5.333	0.588	5.874	505.1
4	5.333	0.628	5.367	461.6
5	5.333	0.678	4.886	420.2
6	5.333	0.658	4.288	368.8
7	5.333	0.673	4.583	394.1
8	5.333	0.651	5.173	444.9
9	5.333	0.632	5.925	509.5
10	5.333	0.603	6.387	549.3
11	5.333	0.519	5.878	505.5
12	5.333	0.496	5.757	495.1

AVE. IT(KWH/DAY)= 5.473 AVE. IT(LANG/DAY)=470.7

LATITUDE(DEG)= -17.300 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	-40.800	0.507	4.333	372.6
2	-40.800	0.520	4.666	401.3
3	-40.800	0.588	5.532	475.7
4	-40.800	0.628	6.069	521.9
5	-40.800	0.678	6.523	561.0
6	-40.800	0.658	6.198	533.1
7	-40.800	0.673	6.388	549.4
8	-40.800	0.651	6.242	536.8
9	-40.800	0.632	5.972	513.6
10	-40.800	0.603	5.419	466.0
11	-40.800	0.519	4.456	383.2
12	-40.800	0.496	4.165	358.2

AVE. IT(KWH/DAY)= 5.497 AVE. IT(LANG/DAY)=472.7

FIGURE H-7 AVERAGE DAILY INSOLATION: BINDURA, ZIMBABWE, 17°18'S 31°20'E

LATITUDE(DEG)= -17.817 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	0.000	0.543	6.198	533.0
2	0.000	0.540	5.942	511.0
3	0.000	0.581	5.884	506.0
4	0.000	0.626	5.547	477.0
5	0.000	0.677	5.163	444.0
6	0.000	0.684	4.779	411.0
7	0.000	0.702	5.093	438.0
8	0.000	0.704	5.849	503.0
9	0.000	0.690	6.616	569.0
10	0.000	0.648	6.895	593.0
11	0.000	0.578	6.500	559.0
12	0.000	0.526	6.035	519.0

AVE. IT(KWH/DAY)= 5.875 AVE. IT(LANG/DAY)=505.2

LATITUDE(DEG)= -17.817 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	-17.817	0.543	5.716	491.6
2	-17.817	0.540	5.693	489.6
3	-17.817	0.581	5.966	513.1
4	-17.817	0.626	6.046	519.9
5	-17.817	0.677	6.039	519.3
6	-17.817	0.684	5.800	498.8
7	-17.817	0.702	6.085	523.3
8	-17.817	0.704	6.579	565.8
9	-17.817	0.690	6.907	594.0
10	-17.817	0.648	6.717	577.7
11	-17.817	0.578	6.037	519.2
12	-17.817	0.526	5.511	473.9

AVE. IT(KWH/DAY)= 6.091 AVE. IT(LANG/DAY)=523.9

LATITUDE(DEG)= -17.817 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	-41.317	0.543	4.603	395.8
2	-41.317	0.540	4.831	415.5
3	-41.317	0.581	5.454	469.0
4	-41.317	0.626	6.034	518.9
5	-41.317	0.677	6.493	558.4
6	-41.317	0.684	6.461	555.6
7	-41.317	0.702	6.678	574.3
8	-41.317	0.704	6.787	583.7
9	-41.317	0.690	6.530	561.6
10	-41.317	0.648	5.801	498.9
11	-41.317	0.578	4.898	421.2
12	-41.317	0.526	4.382	376.9

AVE. IT(KWH/DAY)= 5.746 AVE. IT(LANG/DAY)=494.1

LATITUDE(DEG)= -17.817 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)
1	5.833	0.543	6.275	539.6
2	5.833	0.540	5.940	510.9
3	5.833	0.581	5.768	496.1
4	5.833	0.626	5.296	455.5
5	5.833	0.677	4.794	412.3
6	5.833	0.684	4.370	375.8
7	5.833	0.702	4.687	403.1
8	5.833	0.704	5.516	474.3
9	5.833	0.690	6.416	551.8
10	5.833	0.648	6.851	589.2
11	5.833	0.578	6.564	564.5
12	5.833	0.526	6.131	527.3

AVE. IT(KWH/DAY)= 5.717 AVE. IT(LANG/DAY)=491.7

LATITUDE(DEG)= -17.817 REFLECTION COEF.=0.20

MONTH	TILT(DEG)	KT	IT(KWH/DAY)	IT(LANG/DAY)	S(KWH/DAY)	S(LANG/DAY)
1	5.833	0.543	6.269	539.2	2.448	210.5
2	5.833	0.540	5.941	510.9	2.314	199.0
3	5.833	0.581	5.772	496.4	2.041	175.5
4	-41.317	0.626	6.035	519.0	2.050	176.3
5	-41.317	0.677	6.495	558.6	1.730	148.8
6	-41.317	0.684	6.456	555.2	1.662	142.9
7	-41.317	0.702	6.677	574.2	1.431	123.0
8	-41.317	0.704	6.783	583.3	1.371	117.9
9	-41.317	0.690	6.532	561.8	1.365	117.4
10	5.833	0.648	6.855	589.5	1.861	160.1
11	5.833	0.578	6.568	564.8	2.374	204.2
12	5.833	0.526	6.127	527.0	2.466	212.1

AVE. IT(KWH/DAY)= 6.376 AVE. IT(LANG/DAY)=548.3

FIGURE H-8 AVERAGE DAILY INSOLATION: HARARE, ZIMBABWE, 17°49'S 31°04'E

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16. Abstract

The purpose of this text is to provide the reader with the background, understanding, and computational tools needed to master the practical aspects of PV technology, application, and cost. The focus is on stand-alone, silicon solar cell, flat-plate systems in the range of 1 to 25 kWh/day output. Technology topics covered include operation and performance of each of the major system components (e.g., modules, array, battery, regulators, controls, and instrumentation), safety, installation, operation and maintenance, and electrical loads. Application experience and trends are presented. Indices of electrical service performance - reliability, availability, and voltage control - are discussed, and the known service performance of central station electric grid, diesel-generator, and PV stand-alone systems are compared. PV system sizing methods are reviewed and compared, and a procedure for rapid sizing is described and illustrated by the use of several sample cases. The rapid sizing procedure yields an array and battery size that corresponds to a minimum cost system for a given load requirement, insolation condition, and desired level of service performance. PV system capital cost and levelized energy cost are derived as functions of service performance and insolation. Estimates of future trends in PV system costs are made.

The original text, published in December 1982 as CR-168025, was used in a series of seminars on PV technology conducted by the author in several developing countries during 1983 and 1984. The present edition provides an update and enlargement of the system design and cost chapters.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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